FDL-TDR-64-69

DEFLECTION TRANSMISSION CABLES FOR USE IN THERMAL ENVIRONMENTS IN EXCESS OF 3500°F

TECHNICAL DOCUMENTARY REPORT No. FDL-TDR-64-69

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AIR FORCE FLIGHT DYNAMICS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 1347, Task No. 134702

(Prepared under Contract No. AF 33(657)-11354 by the
Aerojet-General Corporation, Sacramento, California;
Allen T. Green and Richard K. Steele, Authors)

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FOREWORD

This report was prepared by the Aerojet-General Corporation under Contract AF 33(657)-11354. The contract was initiated under Project 1347 - Structural Testing of Flight Vehicles, Task 134702 - Measurement of Structural Response.

The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Research and Technology Division. J. L. Mullineaux was Project Engineer at RTD.

This report concerns work conducted from 1 July 1963 to 31 May 1964.

This work was conducted in the Structures Test Laboratory in the Solid Rocket Plant, Aerojet-General Corporation, Sacramento, California. A. T. Green was Project Engineer, under the direction of R. K. Steele, Assistant Manager, Structures Senior Department. Others who contributed to the project included W. R. Cook, D. M. Gans, J. L. Graham, J. Masters, G. F. McQuilliams.

The material-property studies and the final deflection-link fabrication were performed at Aerojet-General Nucleonics, San Ramon, California, with the assistance of G. Fritzke and J. Rynewicz.

ABSTRACT

A method of transmitting deflections from a test structure at 3500°F to a transducer at room temperature was developed. During high-temperature structural tests, accurate test-specimen deflections can only be determined by use of a test specimen-to-transducer link in which thermal expansion and creep are minimal, to the point of being within the required system accuracy, or accountable. The problems involved in accounting for thermal growths of deflection transmission links used during transient heating and specimen motion directed this program to the development of a system in which thermal growths are minimized.

The deflection-transmission-cable link developed during this program consists of water-cooled Invar tubes in an assembly that is spring-loaded to contact the test specimen through a replaceable polycrystalline alumina ceramic tip (Lucalox). The deflection link was evaluated under static and quasistatic test-specimen heating rates and specimen temperatures to 3500°F and a 1/2-hr exposure time. Total deflection-link growth, internal-wall temperatures, and coolant temperatures were recorded during tests.

Coefficient of thermal expansion and creep tests were measured at elevated temperatures on each material.

The deflection-transmission link as reported herein is capable of transmitting test-specimen motions of 4 in. or less with an accuracy of 0.5% of full scale.

This technical documentary report has been reviewed and is approved.

Holland B. Lowndes Jr

HOLLAND B. LOWNDES, JR.
Actg Chief, Structures Division
Air Force Flight Dynamics Laboratory

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TRADEMARKS

Products referred to in this report are listed below together with their proprietors. When a specific trademarked product has been referred to and used successfully in this program, it is in no way to be construed that it is the only item capable of successful performance.

Many of the products compared in this report were commercial items that were not developed or manufactured to meet any Government specification, to withstand the tests to which they were subjected, or to operate as applied during this study. Any failure to meet the objectives of this study is no reflection on any of the commercial items discussed herein or on any manufacturer.

TRADEMARK	COMPANY
Alumel	Hoskins Manufacturing Company
Chromel	Hoskins Manufacturing Company
Fiberfrax	The Carborundum Company
Invar	Soc. Anon. de Commentry - Fourchambault et Decazeville (Aciéries d' Imphy)
Kovar	Westinghouse Electric Corp.
Lucalox	General Electric Corp.
Negator	Hunter Spring Company
Rodar	Wilbur B. Driver Company
Teflon	E. I. duPont de Nemours & Co., Inc.
Tygon	U.S. Stoneware
Vycor	Corning Glass Works

SECTION 1--INTRODUCTION

During structural tests of flight vehicles that are at elevated temperatures as a result of radiant heating, the test-specimen motion must be determined in order to fully analyze the structural design. Measuring these motions when the test specimen is at a temperature of 3500°F can be exceedingly difficult if any degree of accuracy is required.

Early in the program it was decided that it would be easier to develop a device that minimized thermal growth and creep than to use one that required extensive, and certainly difficult to obtain, correction factors. During test runs, using materials with low thermal coefficients of expansion and stabilizing their temperature with coolant flow has maintained total growths within required limits.

Thermal coefficients of expansion and creep data were obtained on the two basic materials used in the link, and the link itself was tested for total growth under various conditions. These conditions ranged from long-term exposures in helium at temperatures over 3500°F to short-term exposures in air at 3000°F+.

By use of a spring-loading arrangement, the link is always in contact with the test specimen and under a compressive preload. Attachment problems are further minimized by fabricating replaceable contact tips in assorted shapes and sizes to allow for specimen strength and configurations. The contact tips are of a ceramic, which transmits a percentage of infrared radiation and thus alleviates the possibility of localized cold spots on the test specimen.

This report describes the development of the design, the design's initial test verification, and the operational checkout of the final design.

Manuscript released by authors in June 1964 for publication as an RTD Technical Documentary Report.

SECTION 2--BACKGROUND

The primary objective of this program was the analytical and experimental investigation of materials for use as a deflection-transmitting cable link capable of following static or quasi-static mechanical loadings combined with steady-state or transient temperature environments ranging from ambient temperature (80°F ± 20°F) to 3500°F.

On the bases of previous experience and references obtained during the writing of the proposal for this program, it was apparent that selecting one material, determining all its physical properties, and being able to instrument it sufficiently to know where each portion of it was during any given time-temperature-displacement interval was clearly a major task. At this time the decision was made to develop a cooled system that would make use of a material's known properties and to apply this system to transmitting mechanical motions from test specimens at elevated temperatures.

With these thoughts in mind and considering the imposed requirements as set forth by RTD, the following preliminary ideas were evolved. Extensive studies would be required to locate a material that had a low or well-defined thermal coefficient of expansion at the required test temperature, so it would be advantageous to keep the system temperature stabilized. One of the most straightforward means of accomplishing this would be with the use of a fluid coolant such as water. This line of reasoning then led directly to a material with a low thermal coefficient of expansion, such as Invar, which would be cooled to minimize its growth.

The problem now considered was how to put a cold body in contact with a specimen at high temperature and not create a major thermal disturbance at the point of contact. The solution required the use of a replaceable insulating material capable of withstanding severe thermal gradients, so that its contact point with the test specimen would be as close to the test-specimen temperature as practical, and yet the tip attachment to the water-cooled unit would be at a much lower temperature. A new ceramic product, Lucalox, was selected for the first studies. At this time, other factors entered the preliminary design, such as how to attach the system to the test specimen and how much coolant would be required at these temperatures.

SECTION 3--PRELIMINARY DESIGN

A. HEAT TRANSFER

1. Flow Sizing

A preliminary design evaluation was conducted analytically to determine if the proposed line of reasoning would be adequate. At this time, the inlet and outlet flow were sized to determine the exact dimensions required to remain within the outer-diameter (OD) limit of 3/8 in. as established by RTD and yet allow nonrestricted coolant flow.

The following set of simultaneous equations determined the system flow sizings:

$$A_1 = \pi \ (r_1^2 - r_2^2) \tag{1}$$

$$A_2 = \pi \ (r_2^2 - r_3^2) \tag{2}$$

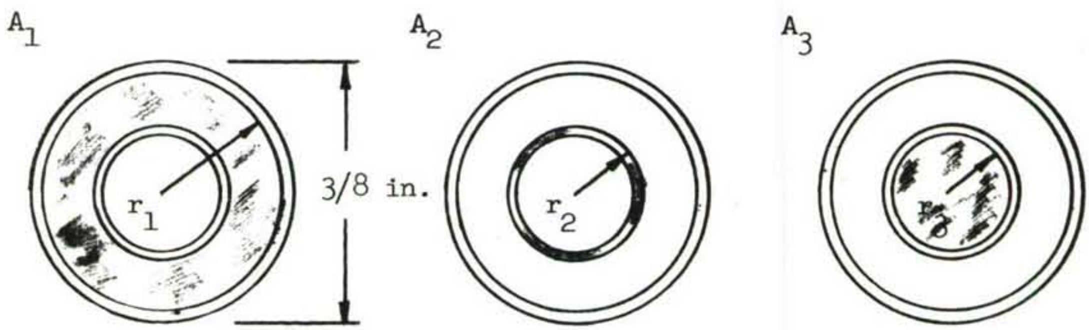
$$A_3 = \pi \ r_3^2 \tag{3}$$

$$A_1 + A_2 + A_3 = \text{total cross-sectional area within a 3/8-in.-OD tube of fixed wall thickness} \tag{4}$$

$$A_1 = A_3 \tag{5}$$

$$r_3 = r_2 - \text{wall thickness of inner tube} \tag{6}$$

Where the areas and radii are representative of:



For a wall thickness of 0.020 in. and a 0.375 in. OD the following set of equations was solved for r_2.

$$A_1 + A_2 + A_3 = \pi \left(\frac{.335}{2}\right)^2 = .0881 \text{ in.}^2$$

Substituting equation 5, we have:

$$A_2 + 2A_3 = .0881$$

Then substituting for A_2 and A_3 (equations 2 and 3) we have:

$\pi(r_2^{\ 2}-r_3^{\ 2})+2\pi r_3^{\ 2} = .0881$ but

$r_3 = r_2-.02$(equation 6)

therefore after substitution and solving:

$r_2^{\ 2}-.02r_2-.0138 = 0$

Using the binomial theorem solution we find

$r_2 = .1279$ hence $r_3 = .1079$

Thus the inner tube was sized at .256 in. OD and .216 in. ID.

2. Thermal Sizing

The preliminary thermal sizing was accomplished by the following analysis.

Heat flux to system:

$$q = .173\,\varepsilon AF\left[\left(\frac{Tw}{100}\right)^4 - \left(\frac{Ts}{100}\right)^4\right] \qquad (7)$$

where: ε = emissivity-assumed value .05

A = exposed cross sectional area =

π (diameter)(length) = $\frac{\pi(.375)4}{144}$ = .0327 ft^2

F = view factor-assumed value .75

T_w = source temperature 5760°R

T_s = specimen temperature 510°R

therefore: $q = .173\,(.05)(.0327)(.75)(11.01x10^6) = 2336\ \frac{Btu}{hr.}$

For a total use time of $\frac{1}{2}$-hr, Q = 1168 Btu total input

Assuming a water temperature rise of 30°F,

$$M = \frac{q}{C_p\ \Delta t} \qquad (8)$$

where: M = mass flow

q = flux input = 2336 Btu/hr

C_p = specific heat of water = 1 Btu/lb-°F

Δt = temperature rise = 30°F

hence: $M = \frac{2336}{1(30)} = 77.8$ lb/hr of water or

9.32 gal/hr water flow required

to keep Δt at 30°F

B. STRESS ANALYSIS OF DEFLECTION LINK

1. Check of Outer Invar Tube

The outer Invar tube has an outer diameter (OD) of 0.375 in. and an inner diameter (ID) of 0.355 in. and is subjected to a maximum pressure of 100 psig.

$$\sigma \text{ hoop} = \frac{pr}{t} = \frac{100(.365)}{.010} = 3650 \text{ psi} \tag{9}$$

where: σ hoop = hoop stress, psi

p = pressure, psi

r = radius, in.

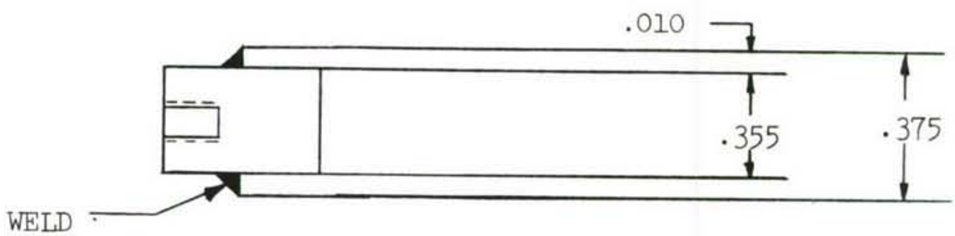
t = wall thickness, in.

$$\text{Margin of Safety (M.S.)} = \frac{\text{tensile allowable}}{\text{stress}} - 1 \tag{10}$$

$$\text{M.S.} = \frac{40{,}000}{3650} - 1 = \text{ample}$$

2. Check of End Seal of Outer Invar Tube

The end of the outer tube is sealed by a fitting welded as shown in the sketch below:



$$\text{Total load per inch of weld} = \frac{pa}{c} \tag{11}$$

where: p = pressure, psi

a = area, in.^{2}: $\left[\frac{\pi\,(\text{diameter})^2}{4}\right]$

c = circumference, in. $\left[\pi\ (\text{diameter})\right]$

therefore: Total load per inch of weld $= \frac{pd}{4} = \frac{100(.355)}{4}$

$= 8.9$ lb/in.

$$\text{Allowable load} = lcF_s \tag{12}$$

where: l = shear length of weld in inches = .707 (thickness)

$= .707(.01)$

c = circumference, in. $= \pi(.355) = 1.11$

F_s = shear allowable, psi = 45,500

therefore: Allowable load = .707(.01)(1.11)45,500 = 357 lb/in.

Margin of Safety (M.S.) $= \frac{357}{8.9} - 1$ = ample

3. Check of Invar Tube for Buckling

The outer Invar tube is in compression, with an unsupported length from the fore of the bushing housing to the test specimen. The maximum load that this column will be subjected to is 5 lb.

The total compressive stress is given by:

$$\sigma = \frac{P}{A} \tag{13}$$

where: P = load in pounds

A = area in square inches, $\frac{\pi\left[(OD)^2-(ID)^2\right]}{4}$

$$= \frac{5}{.011} = 454 \text{ psi}$$

The slenderness ratio for this column is:

$$\frac{L}{r} = \frac{4}{.129} = 31 \tag{14}$$

where: L = unsupported length in inches

r = radius of gyration, inches = $\frac{\sqrt{(OD)^2+(ID)^2}}{4} = .129$

The column is short, and the American Institute of Steel Construction (AISC) specification may be applied for columns with an $\frac{L}{r}$ value less than 120, as follows:

$$\text{Column allowable} = 17{,}000 - .485\,\frac{L^2}{r^2} \tag{15}$$

$$= 17{,}000 - .485\,(31)^2$$

$$= 16{,}534 \text{ psi}$$

Margin of Safety (M.S.) $= \frac{16{,}534}{454} - 1$ = ample

SECTION 4--STAINLESS-STEEL LINK

When the analytical design was completed, an experimental investigation was initiated to study a preliminary design of a deflection link.

Figure 1 shows the link that was fabricated from 304 stainless steel tubing, which consisted of an annular arrangement of tubes to allow water to circulate through the link. The end seal was fabricated from stainless steel shim stock and was silver-soldered in place, using a high-temperature (1100°F) melting-point silver solder.

The unit was pressure-tested to 300 psi of water pressure, as were all subsequent test links.

Two split junction thermocouples (T/C) were spot-welded to the inner wall of the outer tube to measure wall temperatures during test runs. The first T/C's used were of iron-constantan, 30-gage, Teflon-coated wire. These proved satisfactory for only a few test runs, after which the iron leg of the T/C would oxidize from the exposure to water and open the circuit. These thermocouples were then replaced with Chromel/Alumel, 30-gage, Teflon-coated wire, also installed as a spot-welded split junction to the inner wall of the outer tube.

This link was subjected to extensive testing in order to verify as much of the preliminary design estimates as practical. In early test runs, the link was arranged slightly above ($\frac{1}{4}$ in.) and parallel to a stainless-steel plate, which was radiantly heated with an oven consisting of eight 2000-watt, T3 infrared lamps of clear quartz with high-temperature end seals. Specimen temperatures of 1400°F produced an average temperature rise on the probe wall of 22°F when 2 gpm (gallons per minute) of water was passed through the link. The maximum increase in outlet-water temperature was 10°F.

During these runs the water flow was changed from an inlet through the outer tube and exit through the inner, to an inlet through the inner tube and exit through the outer. This change assisted the design in two ways: it eliminated flow instability, which had vibrated the link during early tests; and it provided the end of the link that contacts the specimen with the coolest water.

In subsequent tests this link was used with titanium-plate specimens, as shown in Figure 2. The maximum specimen temperature on the titanium sheet was 2775°F, with a link water-outlet temperature rise of 4°F at a flow of 1.6 gpm. Maximum probe temperature during these runs was 88°F.

The infrared-lamp oven was modified at this time by encasing each lamp in a clear Vycor glass tube, through which air was forced to keep the end seals and exterior of each lamp cool. Air-cooling the infrared lamps substantially increased the total run times at elevated temperatures.

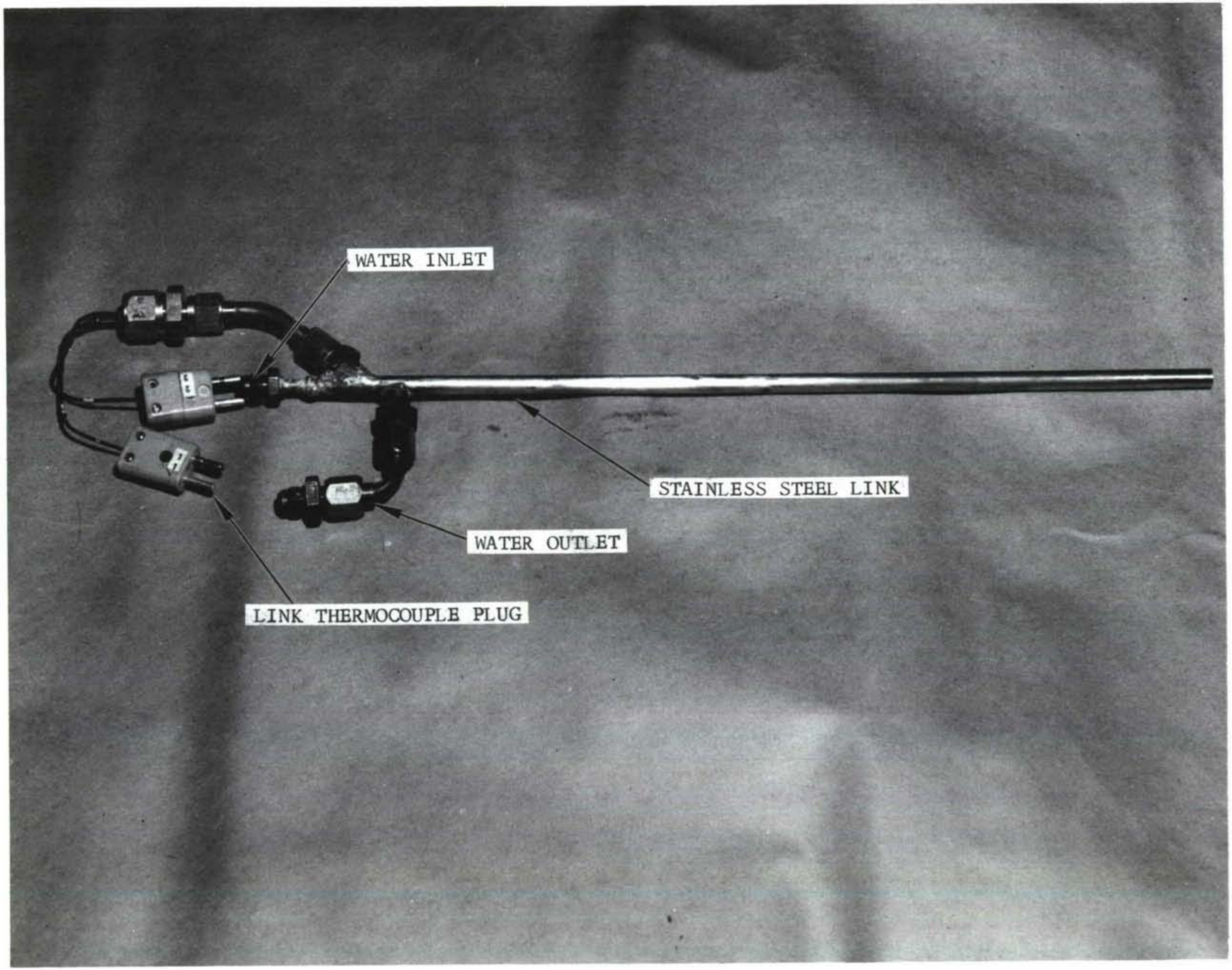


Figure 1. Stainless Steel Preliminary-Design Link

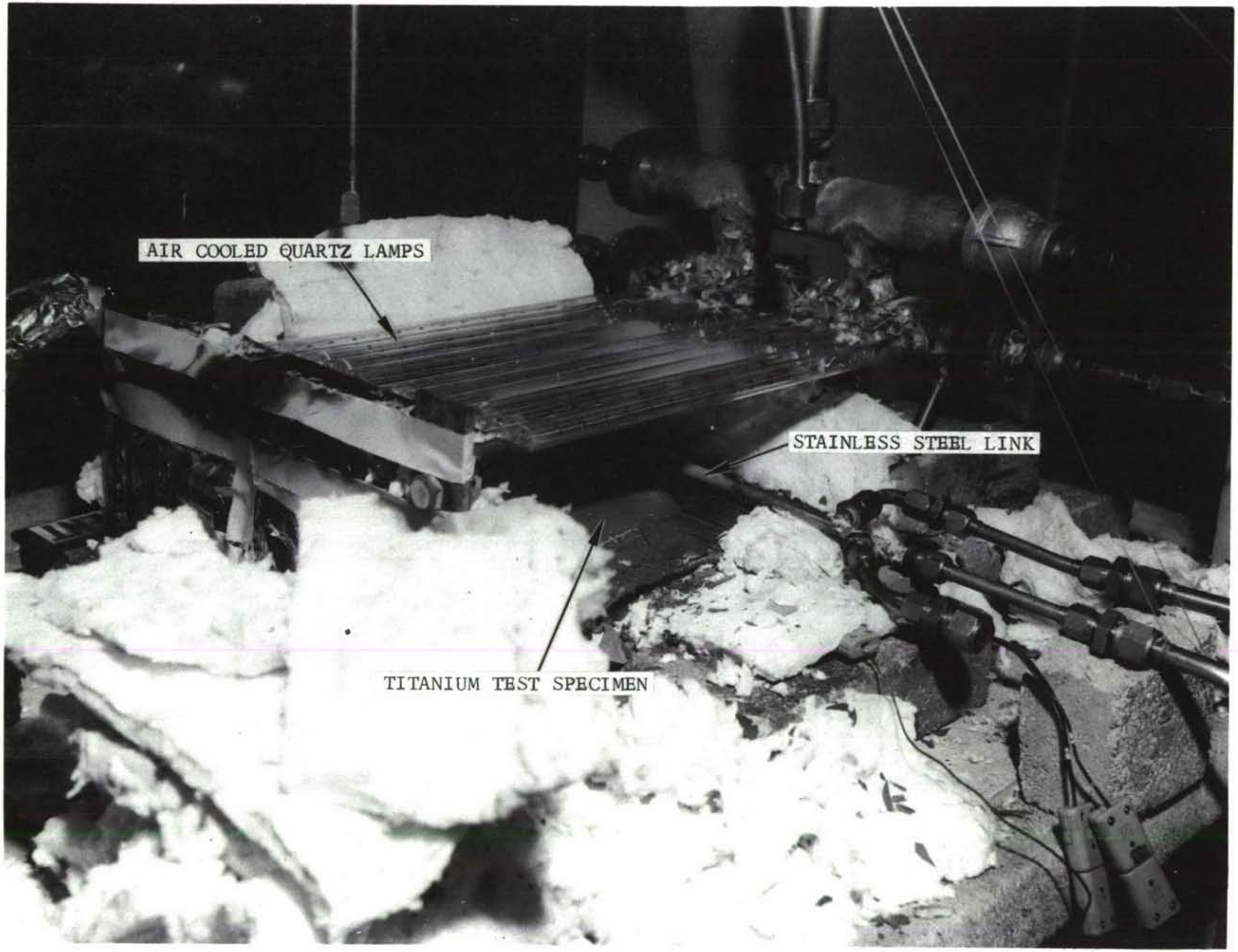


Figure 2. Stainless Steel Link and Radiant Test

Figure 3 shows the first attempt at a link position that passes between the infrared lamps and contacts the test specimen at a right angle. The specimen used here was a 3/8-in.-thick section of a 6-in.-dia carbon cylinder. The carbon specimen was flooded with Argon to minimize oxidation. As with all test specimens, T/C's were installed by drilling small holes into the specimen from the unexposed side and positioning the T/C's within the drilled hole. If clearances existed between the T/C and the drill-hole walls, the T/C was then potted in place with metallic or carbon powder to improve the heat transfer to the T/C.

As test-specimen temperatures increased, the T/C being used to measure the test-specimen temperature was changed accordingly. Chromel/Alumel T/C's were used to 2200°F; platinum/platinum-10% rhodium T/C's to 2800°F; and tungsten-5% rhenium/tungsten-26% rhenium T/C's with 1/16-in.-OD tantalum sheaths and thorium oxide insulation were used to 3500°F.

The carbon specimen was used in a test with the link exposed for 4.5 in., at a normal position to the plane of the lamps. During this test run the carbon specimen was driven beyond 4000°F and held above 3000°F for over $\frac{1}{2}$ hr. Figure 4 shows water inlet and outlet temperature, specimen temperature, and voltage applied to the infrared lamps. The water flow was 1.6 gpm.

While the tests on the stainless-steel link were being completed the Invar tubing ordered for additional prototype design studies was received, fabricated into a deflection link and made ready for testing.

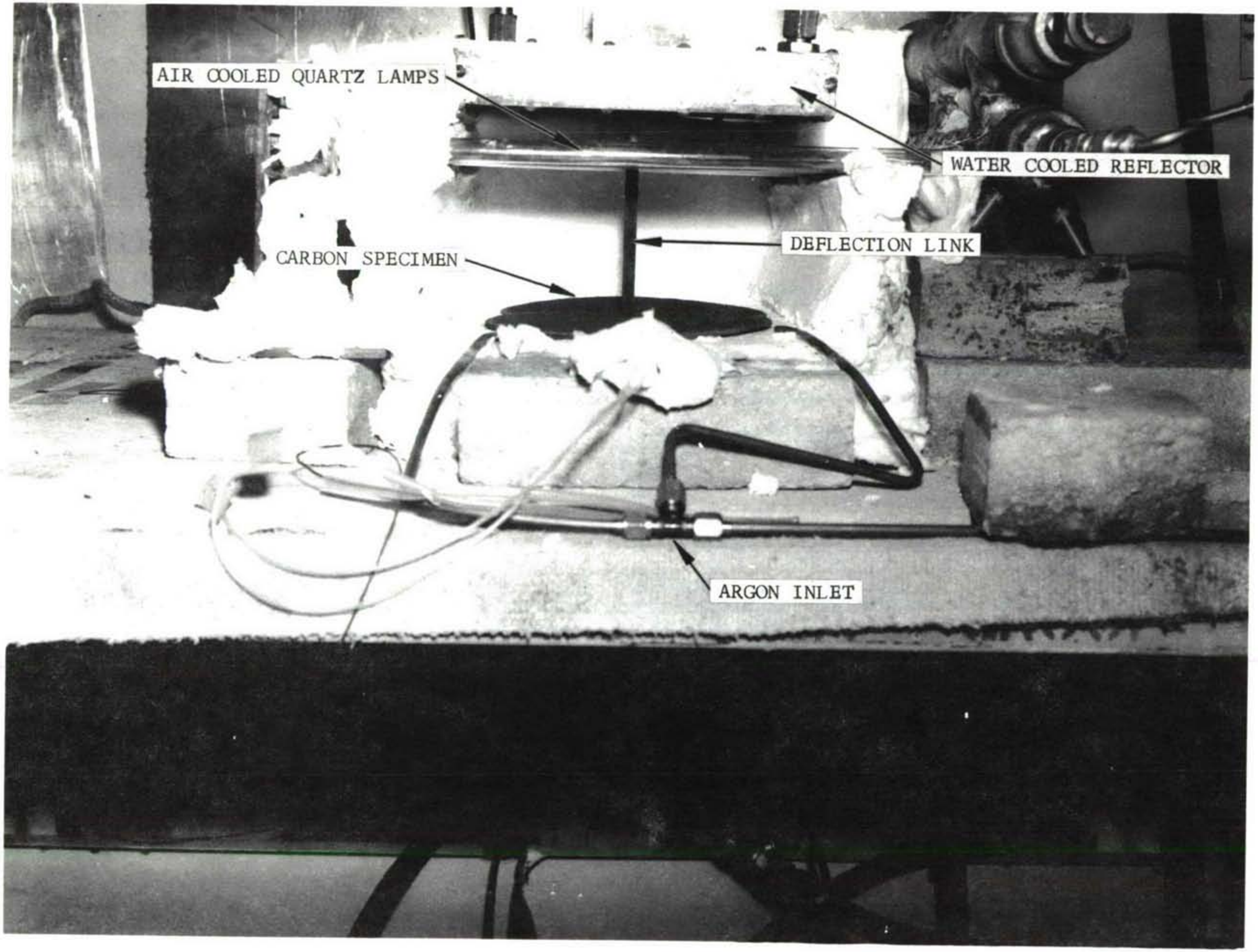


Figure 3. Stainless Steel Link and Carbon Test Specimen

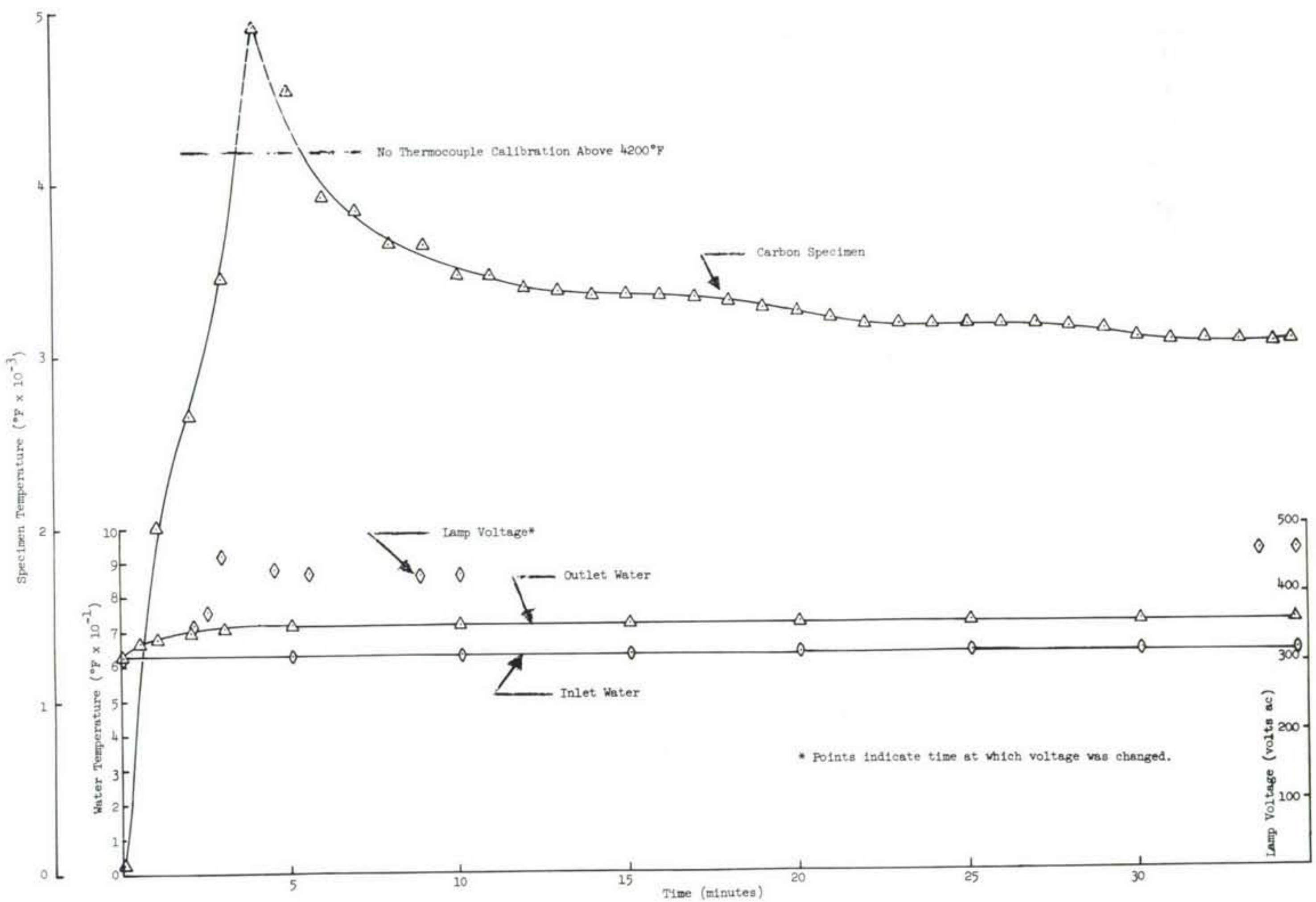


Figure 4. Specimen Temperature vs Time

SECTION 5--INVAR LINK

The selection of Invar for a prototype deflection link followed an extensive search for materials of good mechanical properties and low thermal coefficients of expansion. Many materials can be listed in these categories but of the list Invar appeared most suited for our application. The items most desired at this point were low thermal expansivity and availability of the material.

With the previously described test and others of a similar nature as background, it was decided to fabricate a prototype link from Invar, expose it to an infrared source of 3500°F, and monitor the tube-wall temperature. Therefore, a link similar to the one shown in Figure 1 was fabricated from Invar tubing, sealed with stainless steel shim stock and silver-soldered in place. This link also had two split-junction Chromel/Alumel T/C's installed internally on the inner surface of the outer tube.

This link was then exposed to radiant heating within a carbon-muffle furnace, as illustrated in Figure 5; and the heating element and heat applicator were brought up to a temperature of 3500°F and allowed to soak. The furnace temperature was monitored with an optical pyrometer. The end of the link was in direct contact with the heat applicator during these tests, and approximately 6 in. of the link were exposed to the 3500°F, radiant-source, heating element in a controlled flow helium atmosphere. The maximum rise of the link outlet-water temperature was 24°F at a flow of 2.5 gpm.

With the completion of these tests of preliminary and prototype deflection links, it was decided to go ahead with the final design layout. The practicality of cooling the system to adequately minimize thermal growths had been sufficiently demonstrated. This cooling action was accomplished under normal water pressures and flow rates and on test deflection links where deposits during the test run time had changed the surface from a shiny metallic color to a dull black, thus running nearly the full range of absorptivity.

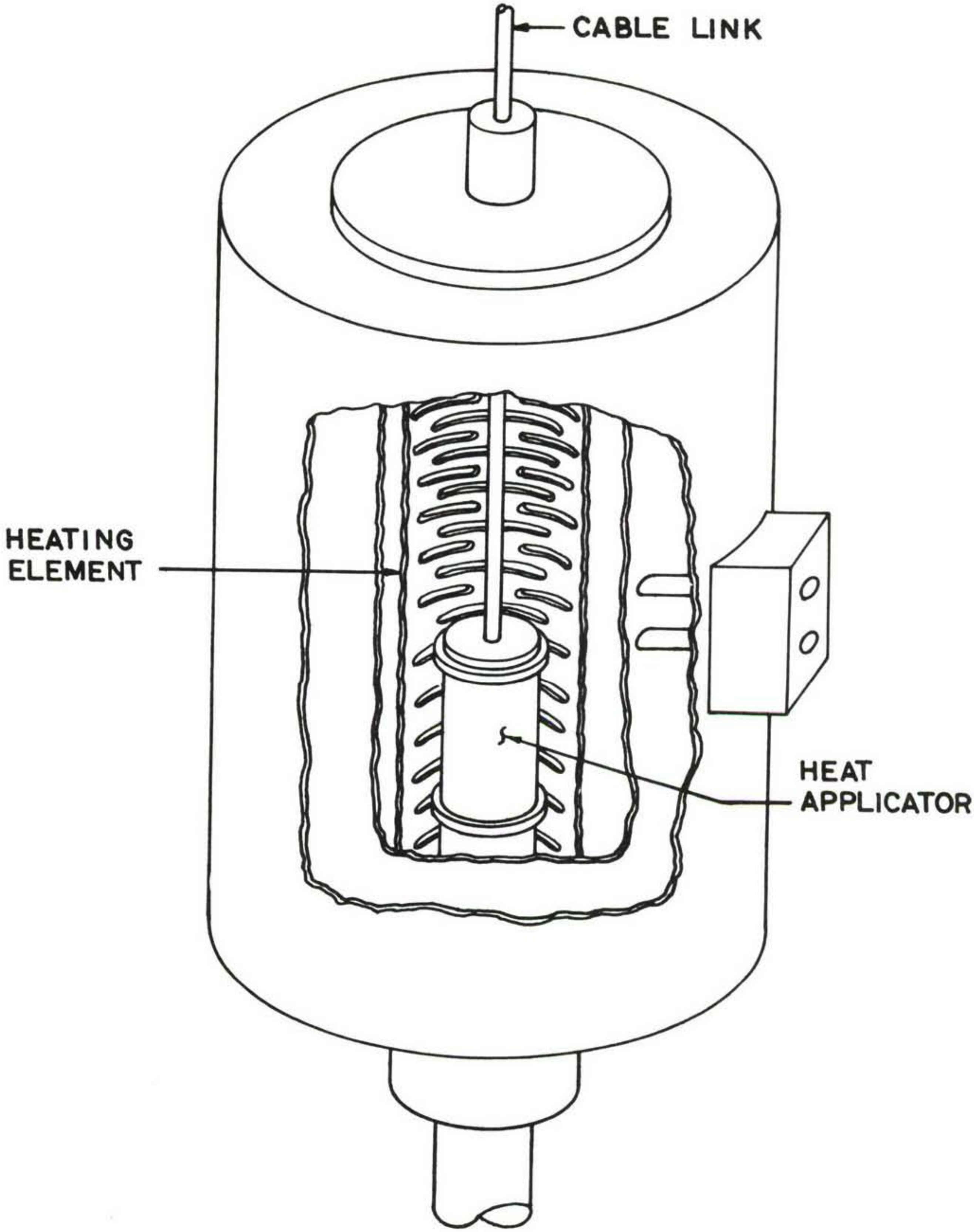


Figure 5. Carbon Muffle Furnace

SECTION 6--SPECIFIC REQUIREMENTS

During the final design period, all specific requirements of RTD were reviewed and the link design was matched to meet each requirement. The majority of the requirements had already been considered in the preliminary analysis; because of our own experiences in radiant-heat testing with quartz infrared lamps, we were well aware of the problems that confront instrumentation engineers on these programs.

The maximum OD of the deflection link had already been set at 3/8 in.; and the maximum length that received radiation presented no problems, as we had already exceeded 4 in. in our preliminary tests. A simple calculation shows that a maximum uncorrected growth of 0.020 in. is all that could be tolerated to remain within 0.5% error of a 4-in. travel. We believed that, with the coolant providing a stable link temperature, this value could be met. The total use time of 5 sec to 30 min would not matter if true temperature stability was obtained.

The requirement to support a constant-tension load of 5 lb presented some reason for thought. If the system were to be in a tensile-load condition, it would require some means of fastening to the test specimen. This, in itself, could require a long, detailed investigation to find satisfactory means of a bonded or mechanical attachment. Even if satisfactory means were determined, it was obvious from a structural test standpoint that they would not only be costly in test setup time and man hours but would certainly produce unwanted effects on many specimens.

With these thoughts in mind, and considering our original idea of an insulator that would contact the test specimen and serve as the connection from the hot specimen to the cool link, we decided that the best attachment should simulate that of the best T/C (i.e., one with zero mass). If we could contact the specimen through an insulating tip, only, and not require any additional means of maintaining this contact during specimen movement, our design would be greatly enhanced.

Constant-force springs gave us the answer to the tension-loading and contacting problem. By using suitably selected constant-force springs attached to the link in the room-temperature area behind the infrared lamp reflectors and opposed to the constant tension loading of the ASD potentiometer, we could keep the link preloaded against the test specimen and would not require additional attachment provisions. In fact, with selected spring forces, it would be possible to vary the link preload, depending on test-specimen or frequency-response requirements. The Hunter Spring Company, manufacturers of Negator Springs, had constant-force extension springs as "off-the-shelf" items. These springs are prestressed strips of spring stock that resist uncoiling with a force that is independent of linear displacement. Using the springs in a back-to-back mounting on either side of the link and opposing the Negator Spring motors in the takeup spools of the RTD potentiometers would provide us with a counterbalance system, one which could be varied to meet any given test requirement.

Because an RTD potentiometer loaned to us for the program would be used in our final operational setup, it was decided to size the Negator Springs in our link design to oppose the spring force in that potentiometer. Sizes of standard-stock extension springs range from $\frac{1}{4}$ to 40 lb; and, if an extreme number of cycles are required, springs are also available with a higher fatigue life. From its relaxed position, the extension spring must be withdrawn at least 1.25 times the drum diameter before developing its full rated load.

Duplicating the laboratory heating setups and test methods of the RTD Facility as closely as possible during our investigations produced only one problem: how to get test-specimen temperatures to 3500°F radiantly with quartz lamps and to hold this temperature for $\frac{1}{2}$ hr. Whereas we had successfully attained temperatures of 3500°F and higher with quartz lamps, we had not been able to hold this value for $\frac{1}{2}$ hr. Keeping the quartz envelope of the lamp below its softening point, and also keeping the end seals of the lamp cool during test runs so that oxidation of the lead-in wire to the filament would not cause lamp failure, has continually been a difficult problem in the aerospace testing field. Considerable time was spent in investigations aimed at prolonging lamp life while operating at 480 v, our maximum available voltage.

Other specific requirements which had to be met were the coefficient of thermal expansion versus temperature, and its deviation for different lots of the same material; thermal elongation versus time at temperature (creep); and expected useful life. While these did not appear to be too important when considered against a stabilized thermal system, we decided to verify vendors' information regarding these parameters.

SECTION 7--MATERIAL SELECTION

Selection of materials for use in the final design was not difficult: we needed a material for the main body of the link that had as its basic property a very low thermal coefficient of expansion; and, for the link tip, we needed a material which would withstand severe temperature gradients, preferably an insulator, one whose melting point was above 3500°F.

A. INVAR

The search for a material with a low thermal coefficient of expansion during the preliminary design period, immediately led us to commercial iron-nickel base alloys such as Invar, Kovar, and Rodar. Within this group, Invar and its variations stand out as possessing the lowest thermal expansivity. Super-Invar, an alloy of 31% nickel plus cobalt, has near-zero expansivity over temperature ranges to about 400°F. While several manufacturers offer Super-Invar as a standard item, in some shapes, none supply thin-wall tubing as a stock item. Tubing fitting our requirements was found available in regular Invar with normal delivery times. Type analysis, physical constants, and mechanical properties of Invar - 36% nickel, and free-cut Invar - 36% nickel + 0.2% selenium (Invar treated for improved machinability), are listed in Table 1.

Mechanical and thermal treatment of Invar can affect its expansion properties. Heat-treatment with rapid cooling can decrease the rate of expansion, while slow cooling can increase it. Cold-working the material will also markedly lower its expansivity. For high-precision work, a stress-relieving heat treatment may be used to stabilize the material and thus various lots of the material may be treated for minimal expansivity.

The heat-treat cycle developed by the Massachusets Institute of Technology appears to combine stability and minimum expansivity. The cycle is as follows:

> (1) heat to 1525°F for 30 min at temperature, (2) water quench, (3) heat to 600°F for 1 hr at temperature, (4) air-cool, (5) heat to 205°F for 48 hr at temperature, and (6) air-cool (Reference 1).

The deflection-link design, completely of Invar with the removal of the ceramic tip, can thus be completely stabilized, and the thermal coefficient of expansion minimized, by a heat-treatment process at any time, if so desired.

The deflection links tested in this program were constructed of Invar - 36% nickel and Invar - 36% nickel + 0.2% selenium. No additional cold-working or stress-relieving was performed on the units; therefore, all expansion data can be considered to be towards the conservative side.

The data from thermal-coefficient-of-expansion tests and creep tests on 3/8-in.-OD Invar tubing, as used in the deflection link, are discussed in detail in Appendix I.

TABLE 1

PROPERTIES OF INVAR

Property	Value: 36% Ni	Value: 35° Ni + 0.2% Se (Free Cut)
Composition		
Carbon	0.12%	0.12%
Manganese	0.35%	0.90%
Silicon	0.30%	0.35%
Nickel	36.00%	36.00%
Iron	Balance	Balance
Selenium		0.20%
Physical Constants		
Specific Gravity	8.05	
Density	0.291 lb per cu in.	
Thermal Conductivity (20-100°C)	72.6 Btu/hr/ft^2/°F/in.	
Electrical Resistivity	495 ohms/cir. mil. ft	
Curie Temperature	280 °C	
Melting Point	1425 °C	
Specific Heat	0.123	
Mechanical Properties (as annealed)		
Tensile Strength	65,000 psi	
Yield Strength	40,000 psi	
Hardness, Rockwell	B-70	
Elongation in 2 in.	35%	
Elastic Modulus	20.5×10^6 psi	

NOTE: Values from Carpenter Steel Company (Reference 2)

TABLE 1 (cont.)

PROPERTIES OF WELD ROD (Stainless Steel 308L)
USED IN DEFLECTION LINK FABRICATION

The 308L stainless steel rod meets the MIL-R-5031A Specification for Type AISI 308 with the following:

Composition	Max Values
Chromium	20%
Nickel	9.5-12%
Sulphur	.03%
Phosphorous	.03%
Silicon	1.0%
Manganese	2.0%
Carbon	.03%

Mechanical Properties	
Tensile Strength	70-80,000 psi
Yield Strength	35,000 psi

NOTE: Values from Metals Handbook (Reference 3)

B. LUCALOX

The material for use as a contact tip had been under consideration during this period. With the announcement by General Electric Co. of a new ceramic material that exhibits most of the physical properties we were interested in, we felt we were close to the final design.

Many materials had been investigated through literature research and other contacts; the new G. E. ceramic material Lucalox appeared closest to satisfy the requirements.

The material is a polycrystalline ceramic composed of a fine-grain, high-purity aluminum oxide (99.9% alumina) that is pressed at room temperature and then fired at a higher-than-usual ceramic firing temperature. As a high-temperature material, it is completely stable and chemically inert to 3450°F and has the composition of a ceramic material, the structure of a metallic material, and a light-transmitting capability unlike any other ceramic.

Lucalox has the remarkable ability to transmit 47% of in-line radiation in the 1.2-micron wave length, the peak spectral energy of a clear-quartz lamp operating at 100% of rated voltage. At higher lamp voltages, such as 200% of rating and a peak spectral-energy wave length of 0.85 microns, it will transmit 38% of the in-line radiation through small sample thicknesses (Reference 2).

The melting point of Lucalox is 3704°F, and, because its crystals are bonded directly to each other, its thermal expansion is uniform in all directions. The material has a modulus of elasticity of 56×10^6 psi and maintains good strength characteristics at elevated temperatures. Some of its physical properties are listed in Table 2. Results of thermal-coefficient-of-expansion and creep testing on a $\frac{1}{4}$-in-dia Lucalox rod are discussed in Appendix II.

The physical properties of Lucalox are determined by two characteristics; density and grain size. Lot variations are controlled by grain size and density checks, and there is no present correlation between these checks and the average physical properties listed.

Other materials considered for use as replaceable contact tips, and in some cases tried during this program, included a castable zirconium oxide, a ceramic adhesive, a castable thorium oxide, and tungsten.

The next most promising material appears to be the castable zirconium oxide. The principal reason for using this refractory is the ability to easily produce link tips of any special design for use in accomplishing various attachment and loading conditions. We did not have a means of sintering the tips in a neutral atmosphere, as required to develop full strength from the material.

All data runs with a tip installed on the link were made with a Lucalox tip.

TABLE 2

PROPERTIES OF LUCALOX

Property	Value
Composition	
Alumina (Al_2O_3)	99.9%
Physical Constants	
Density	3.98 gm/cm^3
Thermal Conductivity (20-100°C)	0.07 $cal/cm^3/sec/°C$
Melting Point	2040°C
Mechanical Properties	
Hardness, Rockwell	A-85
Transverse rupture strength in bending	45,000 psi average
Poisson's ratio	0.205
Modulus of Elasticity, E	56.1×10^6 psi
Modulus of Rigidity, G	23.3×10^6 psi
Bulk Modulus, K	31.7×10^6 psi

NOTE: Values from Lamp Glass Department, General Electric Co. (Reference 4)

SECTION 8--FINAL DESIGN

A design drawing was prepared, which incorporated all the features we had discussed and previously tested. One link was fabricated to the drawing and made ready for extensive testing, in order to include revisions to the final design which were based on actual test usage.

A. STATIC TESTS

The radiant heat, quartz-lamp oven had not yet been completed, so the first series of tests were run in the carbon muffle furnace; the overall system is shown in Figure 6. The carbon-muffle furnace consists of a resistive-heating element, which is a machined-graphite sleeve cylinder that encloses a solid-graphite heat applicator. The temperature of the element is controlled by varying the supply voltage to the heating element; the temperature of the furnace is monitored by either a total-radiation pyrometer or an optical pyrometer. These temperature readings are taken through either of two windows revealing the interior of the furnace.

The furnace is completely evacuated and purged with helium prior to testing. During tests, a continuous positive pressure of helium is allowed to flow through the test section.

Aligning the bottom of the link so that it could be viewed through one of the furnace windows, and optically measuring its movement, provided one-half of the information necessary to establish total growth of the link during test runs. The other measurement of motion was taken from the top of the link at the fitting to which the RTD potentiometer would connect. As shown in Figures 7, 8, and 9, the movement of the upper end of the link was measured with a 0.0001-in. dial gauge, and the lower-end movement of the link was measured with an optical cathetometer capable of direct reading to 0.0001 in.

To assist in making optical measurements on the lower end of the link, fine platinum wires were spot-welded to the periphery of the outer wall at a position on the link that was visible through the upper window of the furnace. A photograph taken while the oven was at temperature clearly illustrates how the optical measurements were made (Figure 10).

Two spot-welded split junction Chromel-Alumel thermocouples were installed on the inner surface of the outer tube. T/C No. 1 was $\frac{1}{2}$-in. above the end of the Invar tube and T/C No. 2 was $3\frac{1}{2}$-in. above the end of the tube.

Test results from these static temperature tests are listed in Tables 3 and 4. Maximum link-length exposed to the radiant furnace at all temperatures was over 6 in. Tests were conducted on the link with and without the ceramic tip installed. A maximum furnace temperature of 3614°F was attained on one of the test runs made with the link and tip installed; the temperature was maintained above 3500°F during this run for 40 min, and total time to 3500°F was 107 min. Similar runs were made with the link installed without its tip; average link growth was 0.0190 in. with tip and 0.0104 in. without tip.

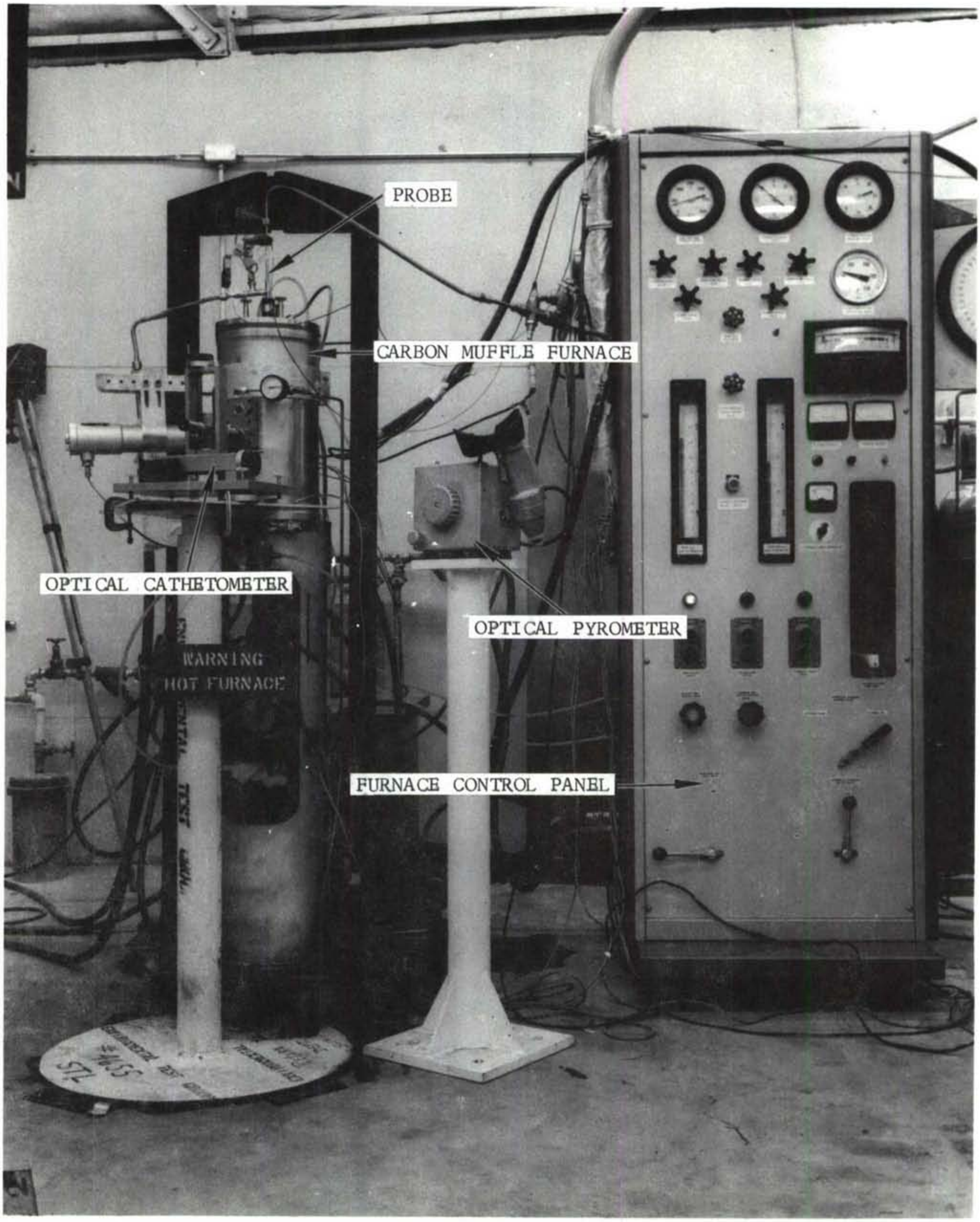


Figure 6. Static-Temperature Test Setup

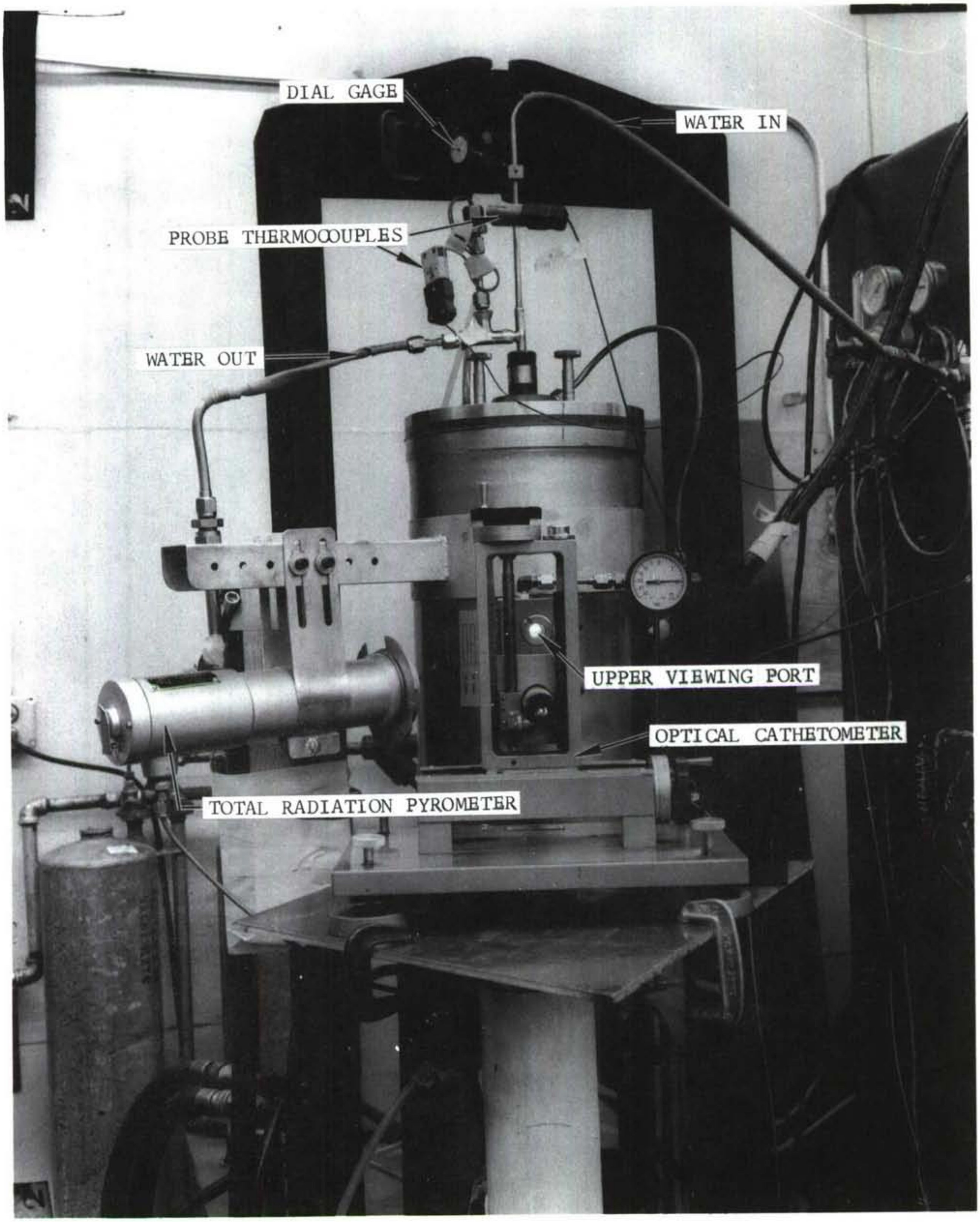


Figure 7. Static-Temperature Test Setup

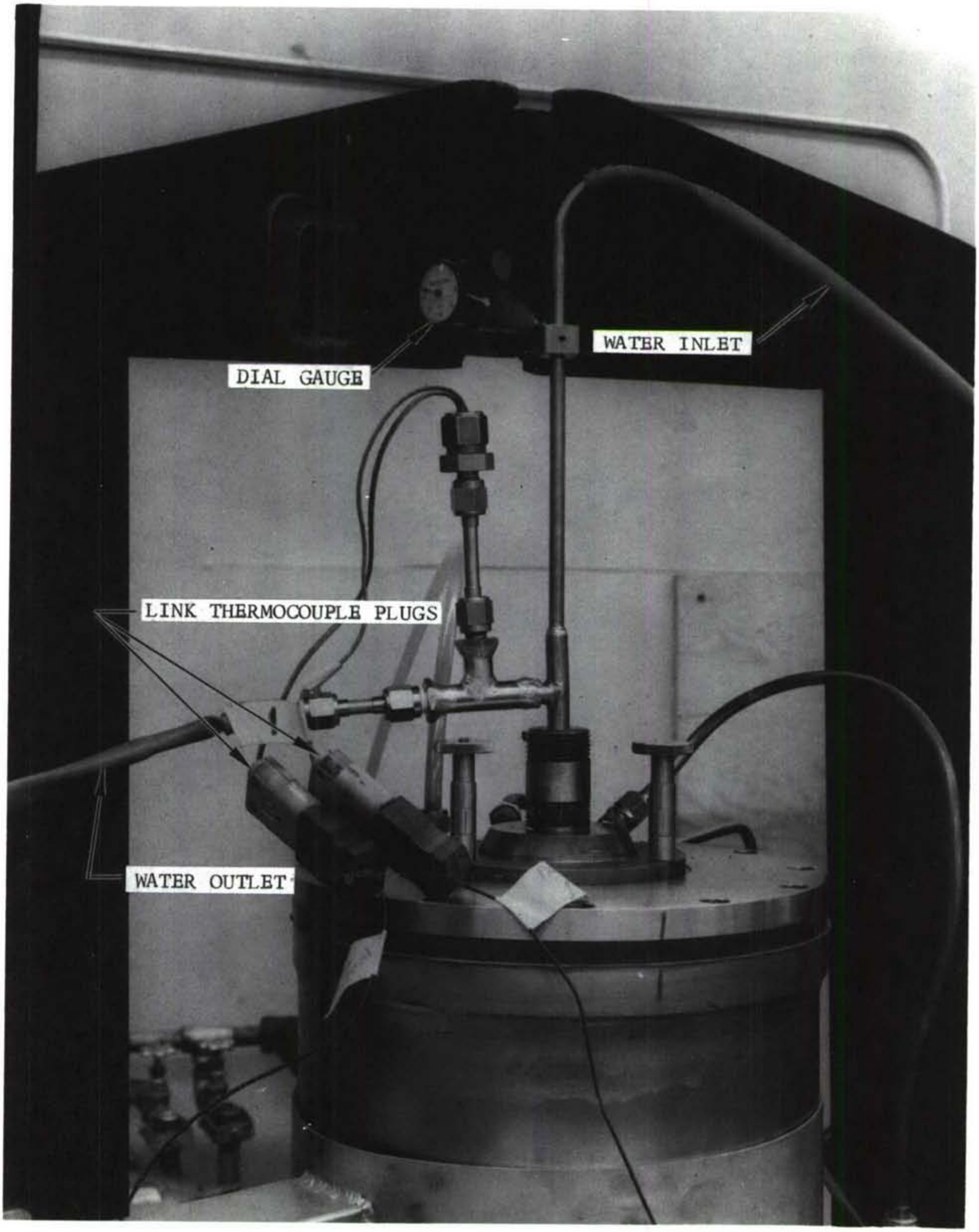


Figure 8. Static-Temperature Test Setup for Upper Link Motion

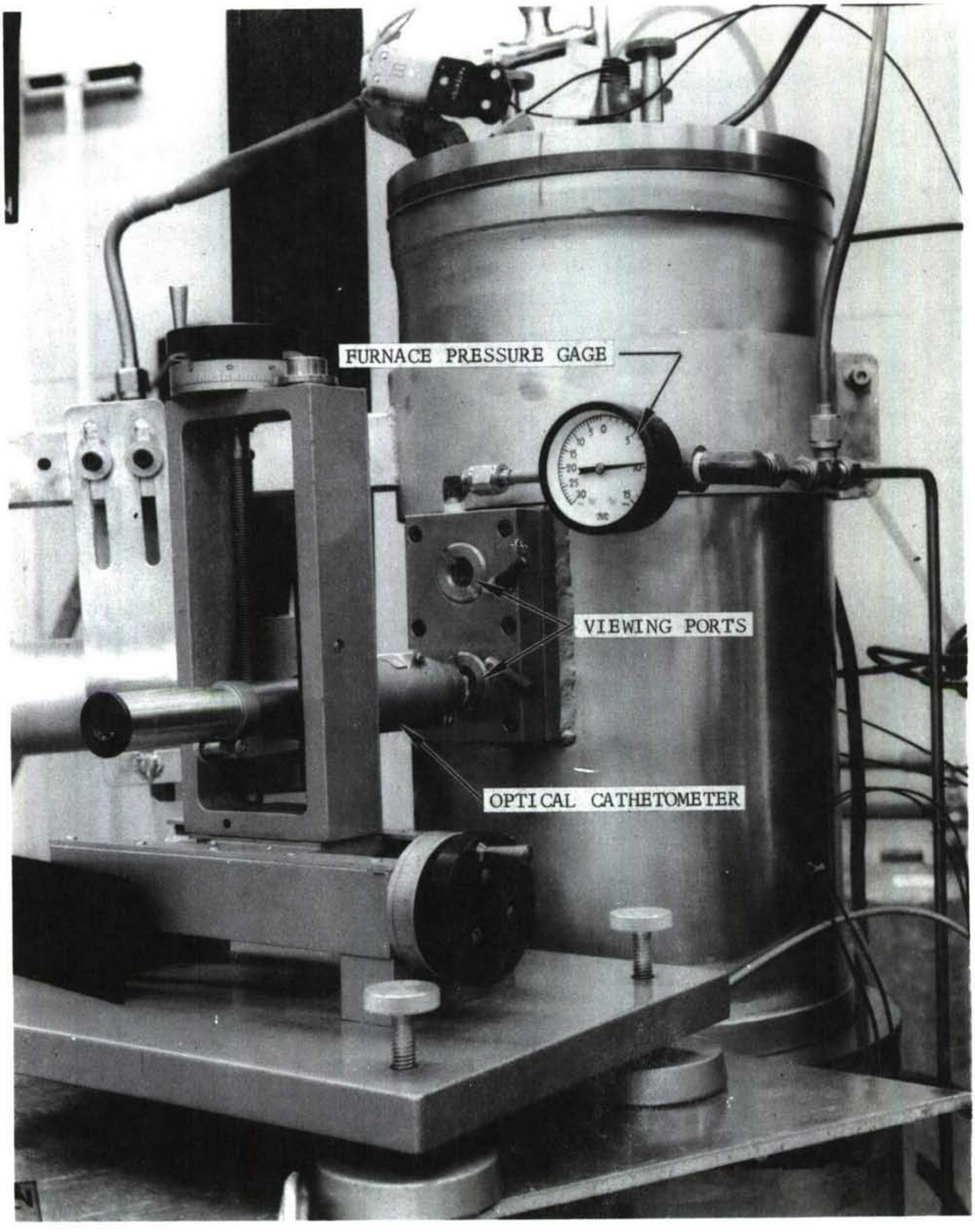


Figure 9. Static-Temperature Test Setup for Lower Link Motion

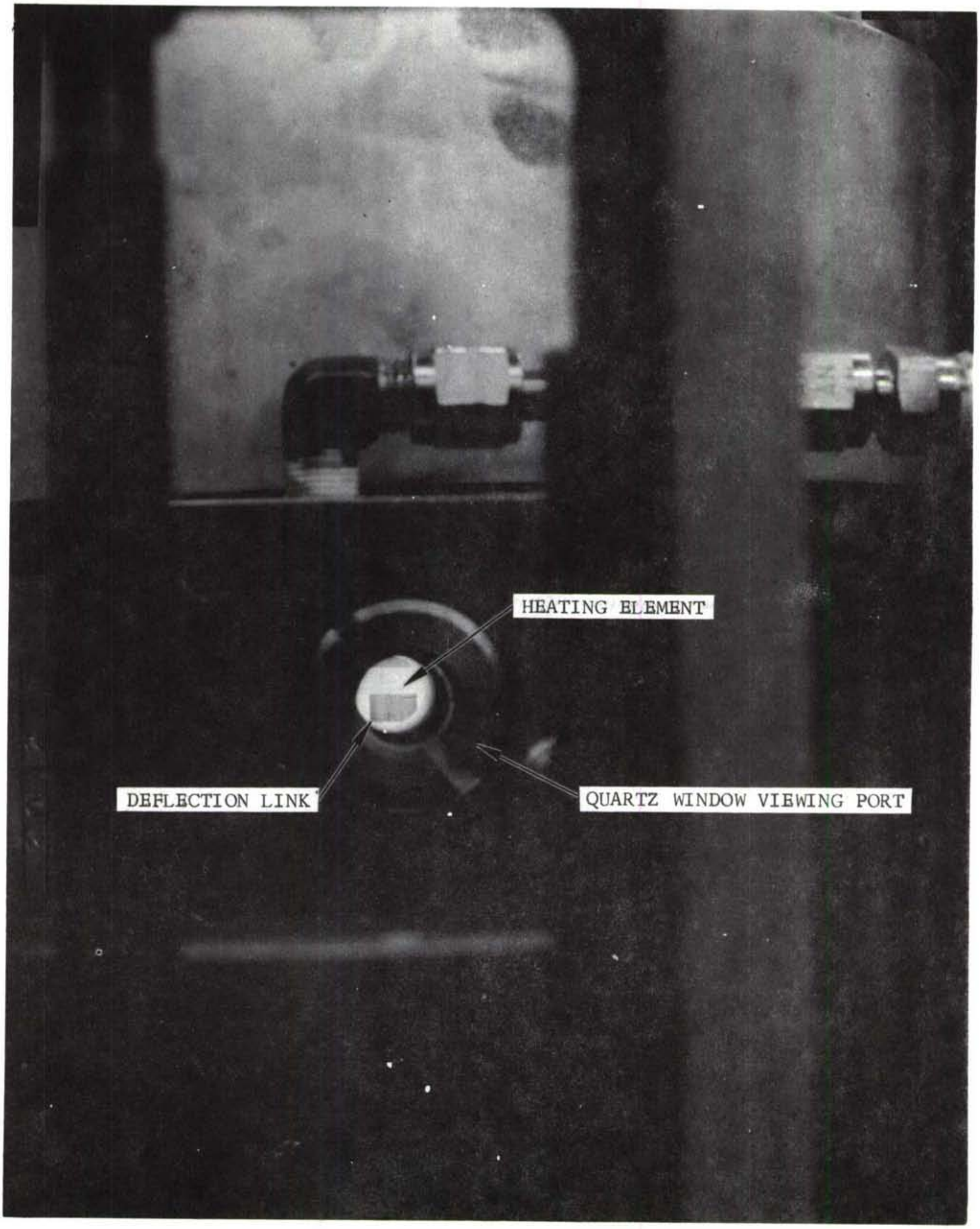


Figure 10. Static-Temperature Test Setup: Link at Temperature

TABLE 3

STATIC-TEMPERATURE TEST RESULTS-LINK AND TIP

Run 1

Furnace Temperature, °F	Elapsed Time, min	Total Link Growth, in.	Link Wall Temperature, (T/C No. 2 at 3-1/2 in.) °F
0	0	0	0
2894	52	.0046	65
3360	64	.0139	75
3484-3614	100-114	.0176	75
3527	124	.0190	75
3380	134	.0179	75

Water flow at 1.9 gpm

Inlet water temperature at 58°F

Run 2 (Two-Point Check)

0	0	0	0
2046	(Not Recorded)	.01255	75
3335	65	.0170	78

Water flow at 1.9 gpm

Inlet water temperature at 58°F

TABLE 4

STATIC TEMPERATURE TEST RESULTS--LINK ONLY

Run 1

Furnace Temperature, °F	Elapsed Time, min	Total Link Growth, in.	Link Wall Temperature, (T/C No. 2 at 3-1/2 in.) °F
0	0	0	60
2349	35	.0106	60
2943	45	.0127	65
3348	(Not recorded)	.0132	70
3538	82	.0122	75
3587	90	.0088	75
3542	108	.0076	78

Water flow at 1.9 gpm

Inlet water temperature at 60°F

Run 2 (One Point Check)

0	0	0	0
3524	255	.0076	83

Water flow at 1.9 gpm

Inlet water temperature at 60°F

Other operational problems arose at this time. On all previous links the coolant lines had been standard hydraulic hoses with AN-type connectors. These were too bulky and rigid for use with the final design, so an investigation was made for a suitable coolant-flow line.

Various flexible and semiflexible lines were investigated with regards to suitability for use with the final deflection link. Table 5 shows results of pressure and flexibility on various types of hoses. A heat-shrinkable tubing (irradiated polyolefin) was tried because of the ease with which connections to the link could be made. The tubing could be slipped over the inlet or outlet water port and shrunk in place to provide a water-tight joint. Tubing of this type was used successfully in temperature tests where deflection link motions were negligible. After these test runs, however, it was decided that this tubing was subject to collapsing when the link motion would produce angular changes on the tubing. A collapsed tube, or lack of cooling water for any reason, would cause a system failure.

A tubing that appeared to be more suitable for our application was then obtained for evaluation. This was a Tygon tubing, a product of U.S. Stoneware. The results of our tests on Tygon tubing are shown in Table 6. We used Tygon type S22-1, a clear flexible tubing that performed completely satisfactorily in all our test runs. A reinforced Tygon tubing, Type B44-4X Inner-Braided, is suggested where water pressures higher than 90 psig are to be used. Both types of Tygon are self-extinguishing, burning only while in direct contact with flame.

B. TRANSIENT TESTS

The tests with radiant-heat quartz lamps were conducted in an air- and water-cooled, quartz, infrared-lamp oven. Figure 11 shows the water-cooled aluminum reflectors, with front removed, and the water-cooled moveable specimen-support table with the carbon test specimen, deflection link, and infrared lamps in place.

Each lamp was individually enclosed in a clear Vycor tube, one end of which was connected to an air manifold and the other end vented to exhaust into the test room. The eleven lamps were 3600-watt, T-3, clear-quartz, infrared lamps with high-temperature, metallic end-seals. The metallic end-seals were removed and each end was potted with a zirconium oxide ceramic cement, which has been proven through past experience to be more durable and to provide greater oxidation protection than other methods.

The lamp voltage was provided from a Research, Incorporated, Thermac Controller with a maximum of 480 available. Rated voltage on the infrared lamps was 230 to 250.

The side reflectors each had inlet provisions for flooding the test specimen and tubes with an inert gas such as argon or helium. During test runs, all oven openings to atmosphere were sealed with layers of Fiberfrax, an alumina-silica fiberous insulating material. The test specimen was also placed on a layer of insulation covering a moveable support table.

TABLE 5

HEAT-SHRINKABLE TUBING TEST

(Irradiated Polyolefin)

Min ID Before Shrinkage, in.	Recovered ID After Shrinkage, in.	Recovered Nominal Wall Thickness, in.	Results of 90 psig Hydrotest	Flexibility Under Pressure	Color
.378	.224	.020	Passed	Good	Blue
.430	.275	.020	Failed	-	Clear
.378	.224	.020	Failed	-	Clear
.430	.275	.020	Passed	Good	Blue
.500	.250	.030	Passed	Very Stiff	Black
.500	.250	.030	Passed	Semi-Rigid	Clear

TABLE 6

PLASTIC TUBING TEST

(Tygon Tubing)

Type	Inside Diameter in.	Outside Diameter in.	Wall Thickness in.	Properties
R2400	3/8	1/2	1/16	Black, semi-rigid
R3400	3/8	5/8	1/8	Black, flexible, Wall too heavy
S22-1*	3/8	9/16	3/32	Clear, flexible
B44-4X** (inner-braided)	3/8	1/2	1/16	Clear, flexible, reinforced

* Used in all deflection-link operational tests
**Recommended where water pressure exceeds 90 psig

NOTE: All types were self-extinguishing, burning only while in direct contact with flame.

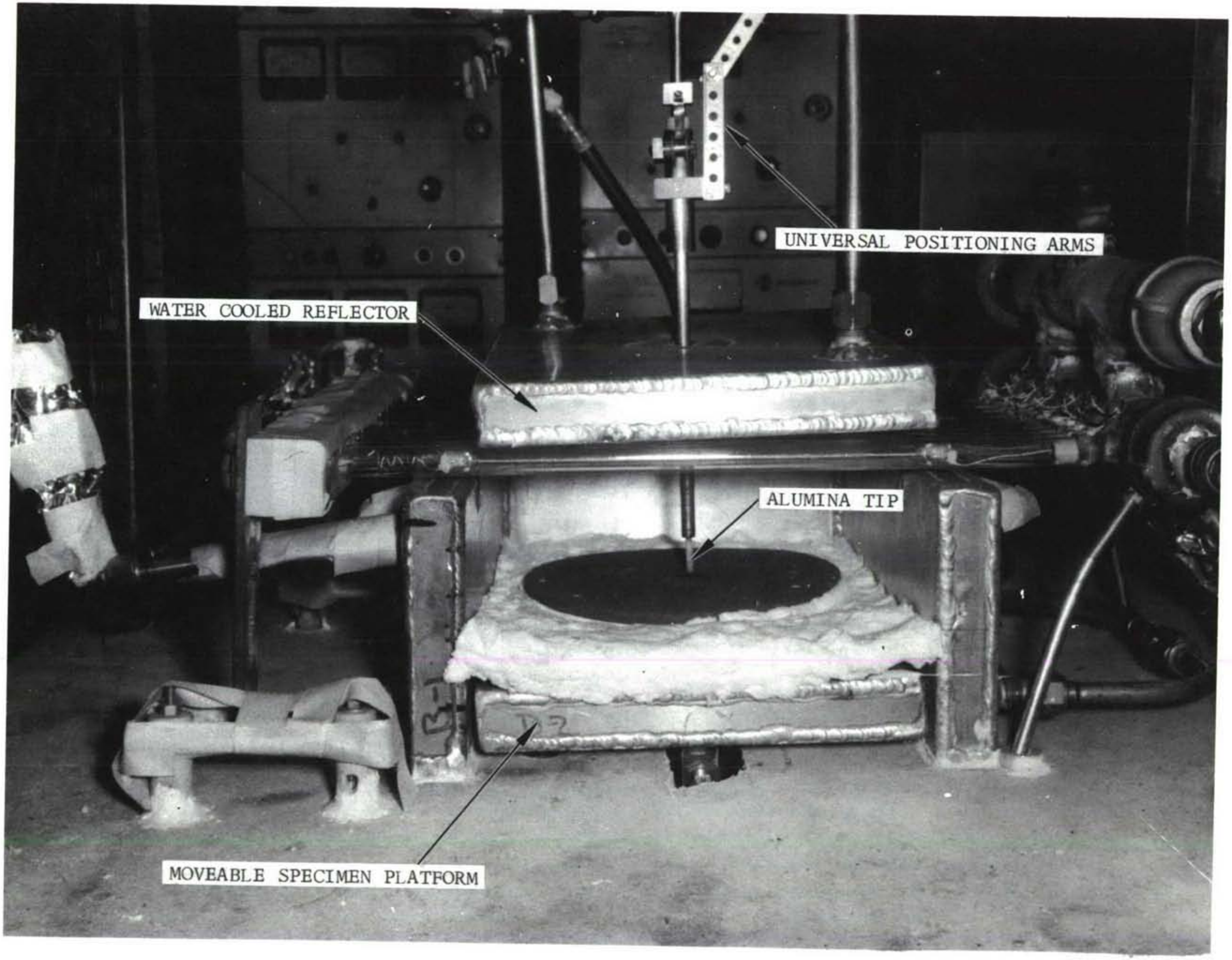


Figure 11. Transient-Temperature Test Setup

A cross-section photograph of the moveable specimen table, drive screw jack, reversible DC motor, and instrumentation is shown in Figure 12. The variable-speed motor would drive the test specimen from a position 4.5 in. below the lamps to full travel upward to 0.1 in. below the lamps. This system was used to program specimen-link movement as recorded and displayed in Figures 13 and 14. These motions were made when the test specimen was at the temperatures noted.

A schematic of all instrumentation which was recorded during test runs is shown in Figure 15. Total link growth was obtained by measuring the upper-end growth with a 0.0001-in. dial gage, and specimen motion was measured with a linear variable differential transformer (LVDT) calibrated in 0.0001-in. increments. Tables 7 through 12 list all pertinent information recorded during these test runs at the various test-specimen positions beneath the lamps.

Total link growths were well within the required limits for all tests conducted. One-half-hour test runs were made with test-specimen temperatures above 3000°F on two occasions. Only during prototype testing was a test-specimen temperature above 3500°F with quartz-lamp heating.

Test-specimen temperatures are dependent on many things, some of these being size, color, thermal conductivity, radiant-source temperature, and radiant-transfer efficiency. Earlier test runs on smaller-mass test specimens had demonstrated that under proper conditions it is feasible to attain temperatures ranging above 3500°F with quartz infrared lamps. Holding specimen temperatures at 3500°F for $\frac{1}{2}$-hr test times, while not to be classified impossible, would require extensive development and be greatly dependent on specimen size.

Because the link had been subjected to radiant temperatures above 3500°F and to run times exceeding $\frac{1}{2}$ hr in the carbon-muffle furnace, and because in all cases in which total growth had been measured it was within 0.5% of full scale, the program was considered to be accomplished.

The final deflection link is shown in Figures 16, 17, and 18. In Figures 16 and 17, the deflection links are shown with ceramic tips installed in place; sample replaceable tips are shown in the background in each figure. Figure 18 shows the link counterbalance and positioning arms.

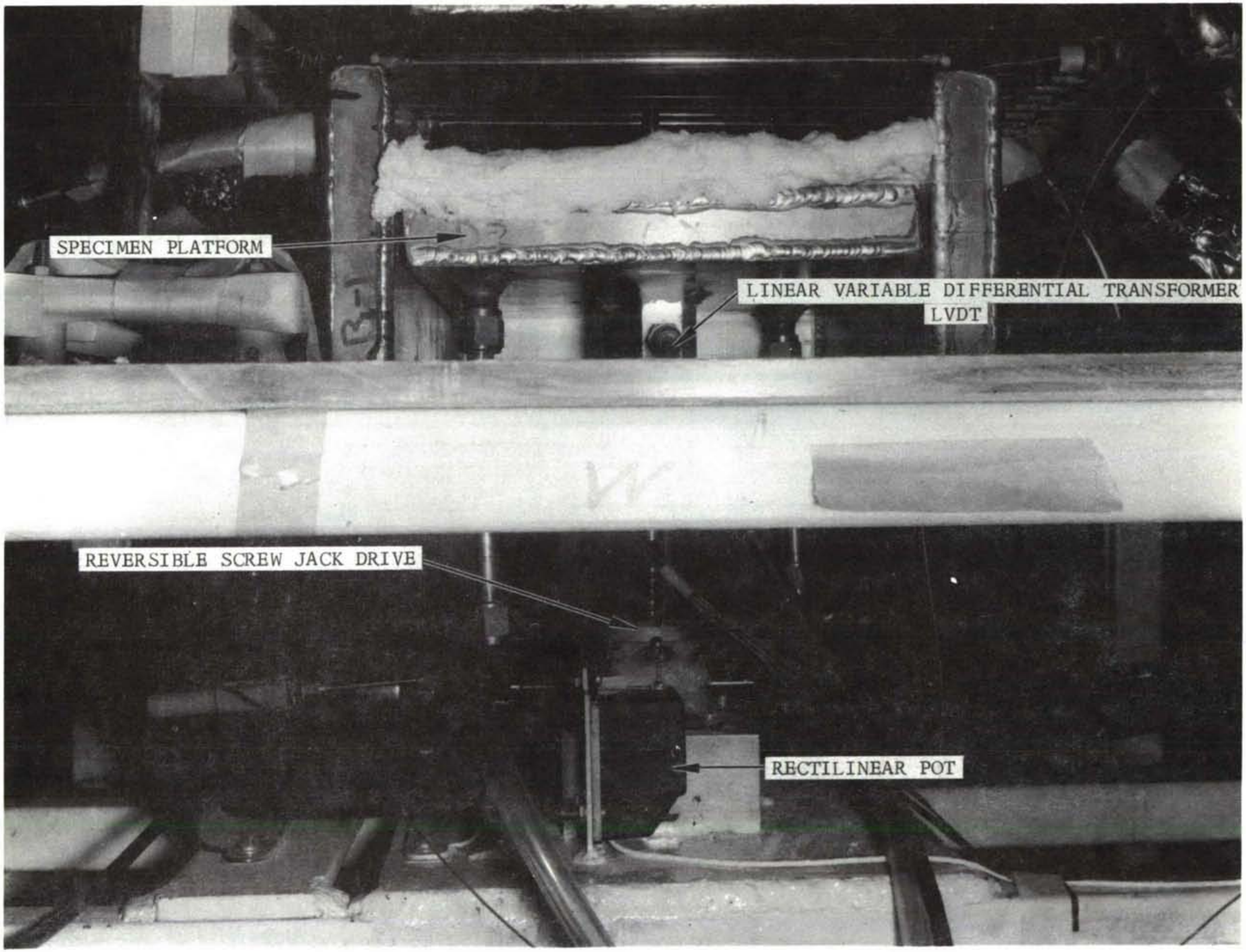


Figure 12. Transient-Temperature Test Setup - Test Specimen Drive

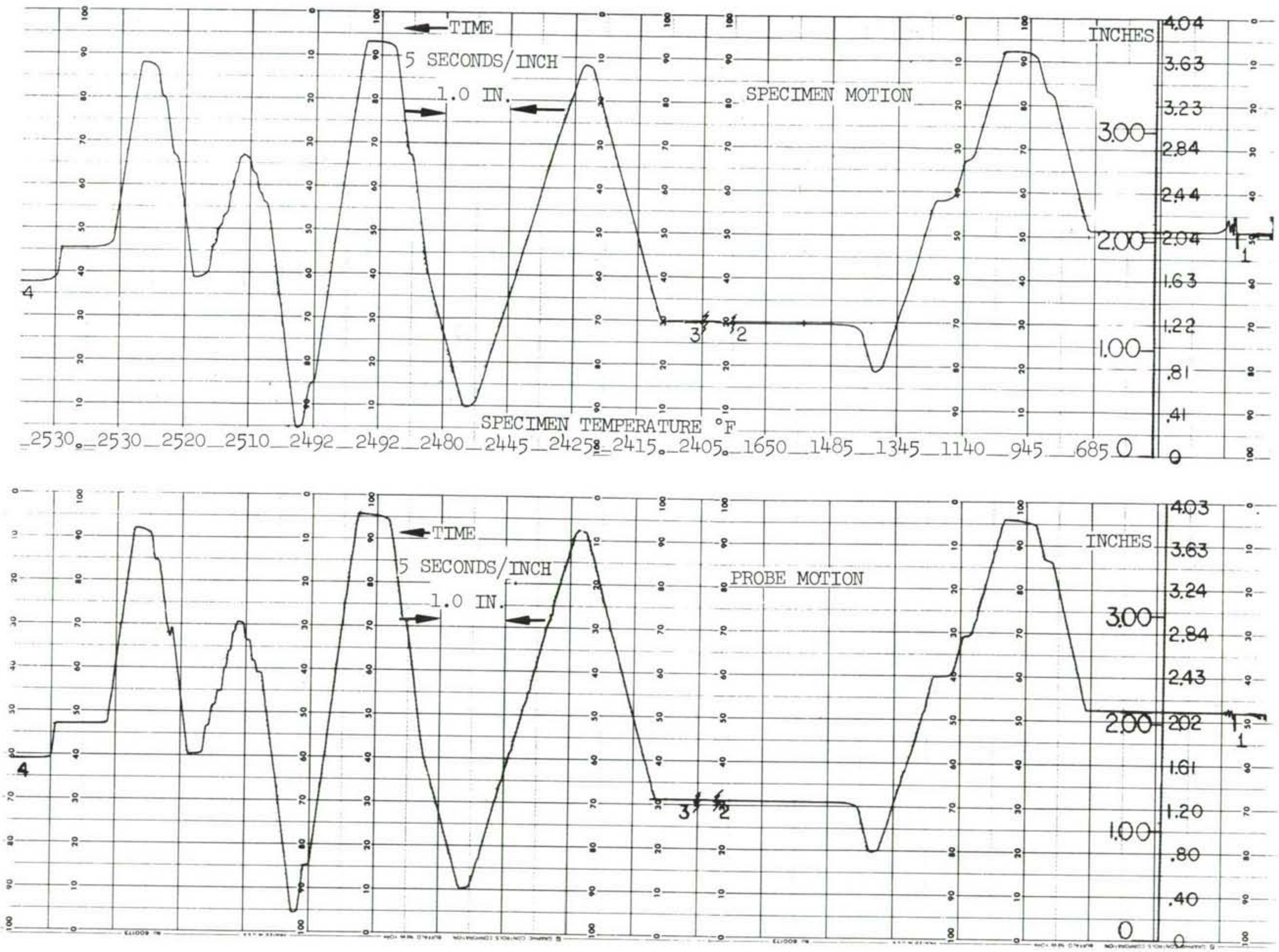


Figure 13. Deflection-Link and Test-Specimen Motion at Temperature (First Comparison)

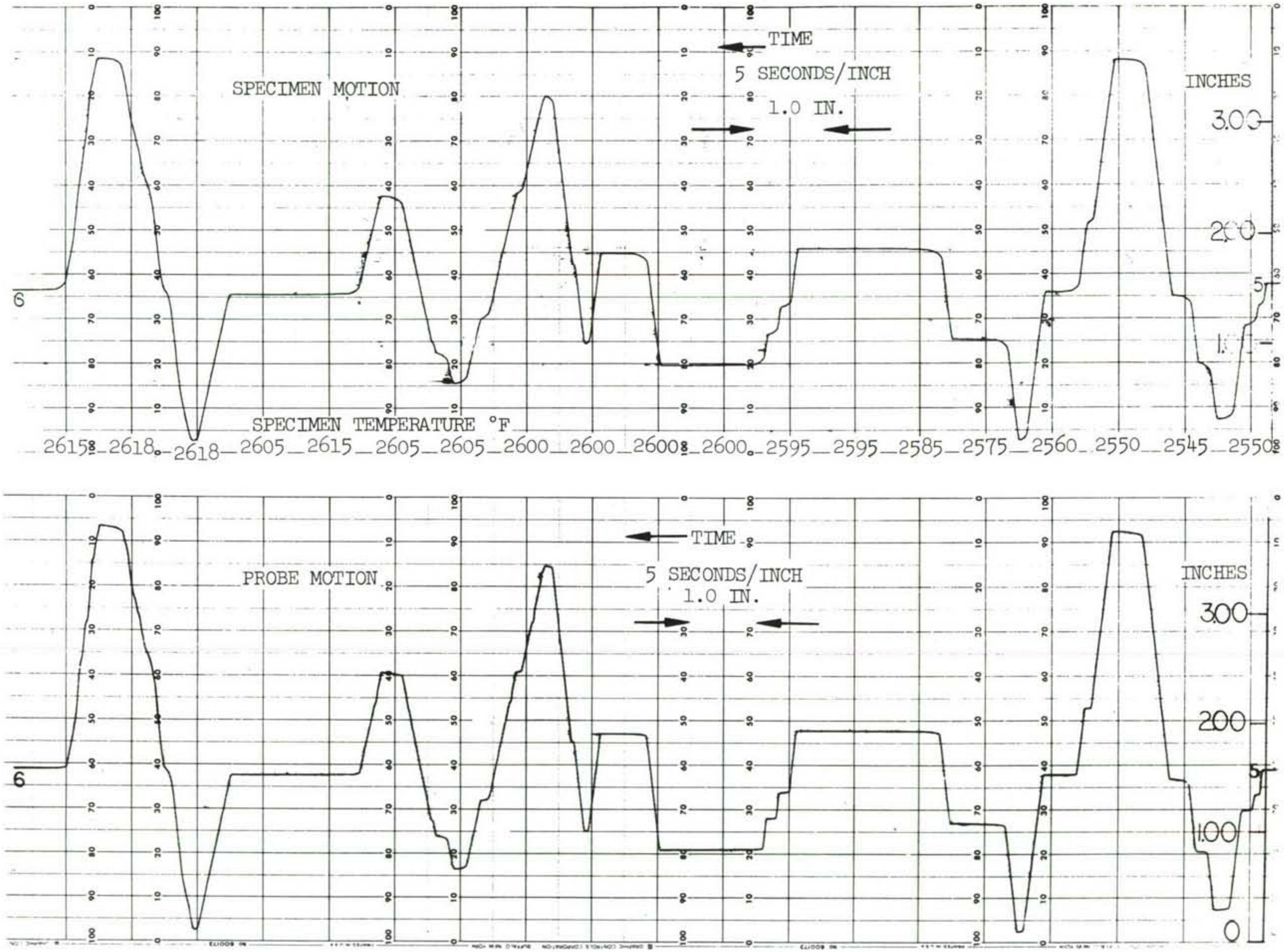


Figure 14. Deflection-Link and Test-Specimen Motion at Temperature (Second Comparison)

TABLE 7

CHECKOUT OF TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 1.0 INCH BELOW LAMPS

	Instrument No.								
Time in Seconds	1	2	3	4	5	6	7	8	9
	Temperature in °F								
0	50	50	63	50	180	188	200	188	150
10	55		63		185	210	320	305	315
20	55		63		230	345	380	395	405
30	58		63		320	395	490	440	535
40	58		63		355	475	620	530	695
50	60		65		430	645	740	635	820
60	65		65		520	770	865	770	955
70	65		65		620	885	1000	890	1095
80	65		65		745	965	1115	1025	1235
90	65		65		860	1125	1245	1140	1350
100	65		65		970	1265	1365	1255	1480
110	65		65		1125	1375	1475	1380	1595
120	65		65		1285	1475	1598	1500	1695
130	65		65		1390	1585	1665	1605	1820
140	65		65		1472	1655	1815	1715	1910
150	70		65		1560	1735	1900	1810	1995
160	70		64		1620	1830	1995	1875	2015
170	70		63		1675	1900	2092	2045	2115
180	70		62		1720	1975	2175	2015	2160
190	75		62		1790	2045	2225	2055	2240
200	75		62		1840	2125	2300	2145	2310
210	80		62		1885	2180	2385	2205	2375
220	80		63		1950	2210	2425	2260	2425
230	80		64		2015	2245	2490	2355	2490
240	80		64		2075	2315	2540	2415	2515
250	80		64		2150	2350	2595	2475	2580
260	80		64		2220	2395	2640	2535	2600
270	80		65		2305	2475	2705	2580	2650
280	80		65		2420	2535	2760	2620	2715
290	80		66		2480	2562	2805	2700	2760
300	82		66		2535	2535	2855	2740	2810
310	85		67		2615	2565	2900	2795	2880
330	90		67		2685	2565	2915	2840	2920
340	90		67		2730	2590	2978	2900	2965
350	100		66		2790	2610	3020	2940	3020
360	100		66		2840	2685	3070	2975	3040
370	100		65		2910	2700	3115	3020	3060
380	103		65		3055	2710	3145	3075	3140
390	105		65		3105	2710	3160	3115	3155
400	110		65		3075	2710	3170	3145	3170
410	110		65		3090	2750	3200	3165	3190
420	110		65		3110	2740	3200	3170	3205
430	113		65		3125	2740	3205	3195	3205
		50		50					

TABLE 8

TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 1.0 INCH, LINK AND TIP

Time in Seconds	1	2	3	4	5	6	7	8	9	10	11
	Instrument No. Temperature in °F									Motion in in.	
0	60	60	47	47	270	360	420	455	450	.0000	.0000
5	70		47		570	660	785	830	815		
10	80		47		908	1030	1168	1250	1300		
15	90		48		1220	1380	1575	1630	1715		
20	100		48		1515	1800	1970	2040	2100		
25	110		48		1865	2150	2315	2382	2415		
30	115		49		2150	2420	2540	2595	2585		
35	120		50		2255	2450	2550	2580	2540		
40	100	60	50	47	2340	2515	2580	2595	2550	-.0112	+.0030
45					2410	2515	2565	2540	2550	(.0142) (Total Growth)	

TABLE 9

TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 3.0 INCHES, LINK AND TIP

Time in Seconds	Instrument No. 1	2	3	4	6	7	8	9	10	11
	Temperature in °F								Motion in in.	
0	60	60	58	58	70	70	70	70	.0000	.0000
5	60	60	58		70	70	70	70		
10	65	65	58		210	315	358	210		
15	75	70	58		530	635	675	535		
20	80	70	59		890	1010	1090	935		
25	80	75	59		1270	1375	1460	1300		
30	80	75	59		1615	1725	1810	1655		
35	85	75	59		1900	2010	2095	1910		
40	80	75	60	58	2110	2210	2280	2105	-.0122	+.0002
					2152	2255		2155	(.0124) (Total Growth)	

TABLE 10

TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 1.0 INCH, LINK ONLY

Time in Seconds	Instrument No. 1	2	3	4	6	7	8	9	10	11
	Temperature in °F								Motion in in.	
0	60	60	60	56	70	70	70	70	.0000	.0000
5	75	60			230	325	338	325		
10	80	60			678	830	838	865		
15	80	60			1075	1260	1295	1330		
20	80	60			1430	1610	1665	1745		
25	85	60			1815	2000	2050	2110		
30	90	60			2115	2320	2385	2348		
35	100	65			2395	2585	2605	2500		
40	105	65			2595	2755	2780	2732		
45	110	65			2755	2885	2920	2845		
50	115	65	60	56	2885	3020	3020	2900	-.0085	+.0040
									(.0125) (Total Growth)	

TABLE 11

TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 1.0 INCH, LINK ONLY

Time in Seconds	Instrument No. 1	2	3	4	6	7	8	9	10	11
	Temperature in °F								Motion in in.	
0	60	60	56	56	70	70	70	70	.0000	.0000
5	60				130	200	160	170		
10	65				210	325	210	230		
15	70				410	530	440	485		
20	70				640	780	700	750		
25	75				910	1080	1010	1080		
30	80		56		1245	1465	1365	1495		
35	85				1610	1870	1785	1890		
40	90				2005	2215	2160	2215		
45	95				2280	2510	2475	2445		
50	100				2540	2705	2690	2615		
55	105				2715	2875	2825	2735		
60	110		57		2825	2965	2955	2825		
65	110				2920	3045	3045	2915		
70	115				2975	3085	3085	3030		
75	110				3020	3125	3140	3085		
80	110				3060	3145	3145	3140		
85	110				2965	2975	3055	2945	-.0130	+.0037
90	110	65	58	56						

(.0167)
(Total Growth)

TABLE 12

TRANSIENT-TEMPERATURE TEST RESULTS
WITH SPECIMEN AT 3.0 INCHES, LINK ONLY

Time in Seconds	Instrument No. 1	2	3	4	6	7	8	9	10	11
	Temperature in °F								Motion in in.	
0	60	60	65	55	70	70	70	70	.0000	.0000
5	60				75	75	75	75		
10	70				310	365	420	400		
15	70				625	735	820	780		
20	75		65		955	1090	1165	1095		
25	75		66		1275	1400	1480	1398		
30			66		1565	1710	1800	1700		
35			66		1815	1985	2040	1950		
40		60	67		2035	2185	2225	2110		
45		70	67		2205	2345	2395	2450		
50		70	67		2328	2475	2515	2365		
55	75	70	68	55	2435	2585	2595	2425	-.0077	+.0002
									(.0079) (Total Growth)	

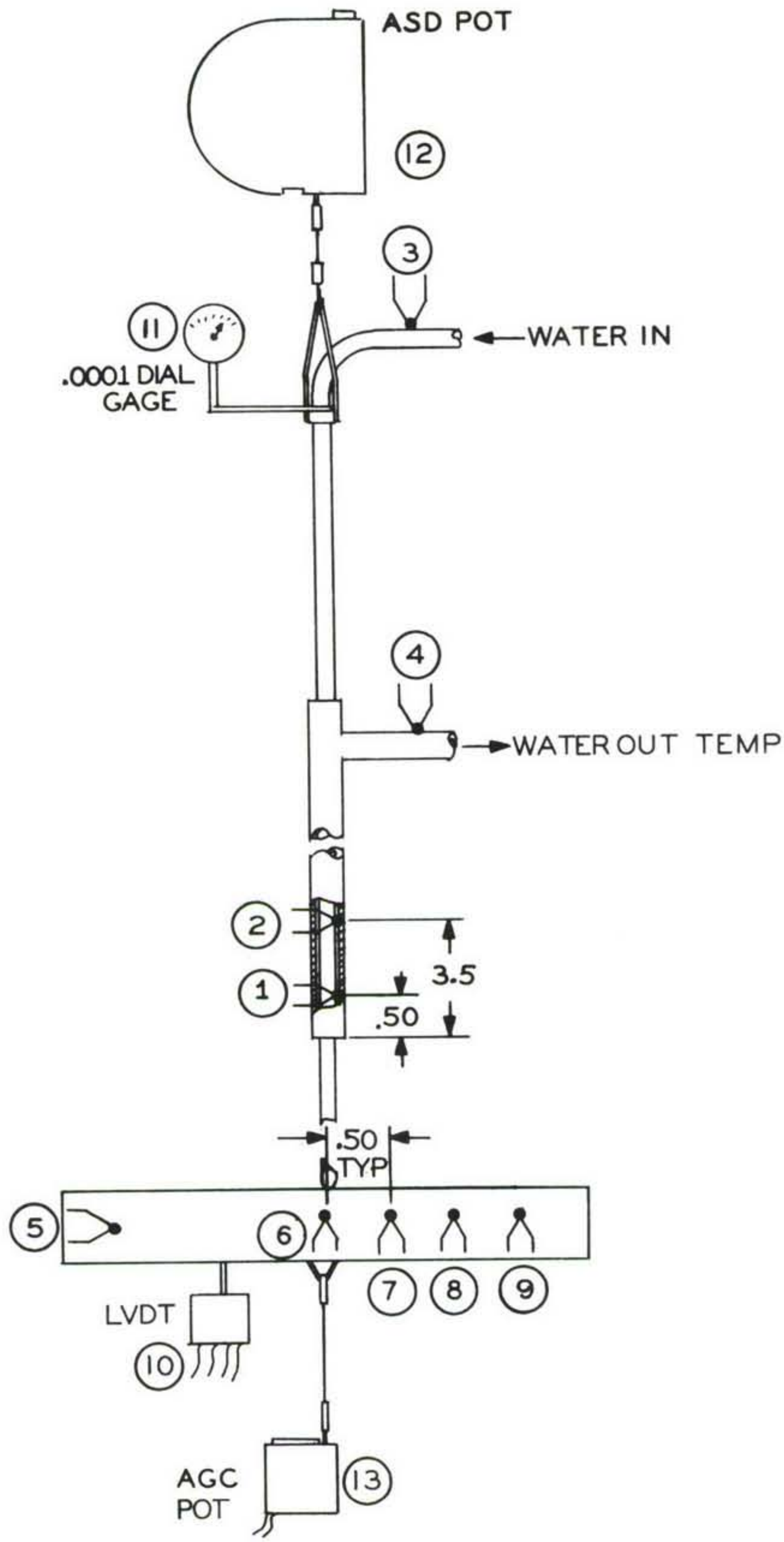


Figure 15. Instrumentation Location

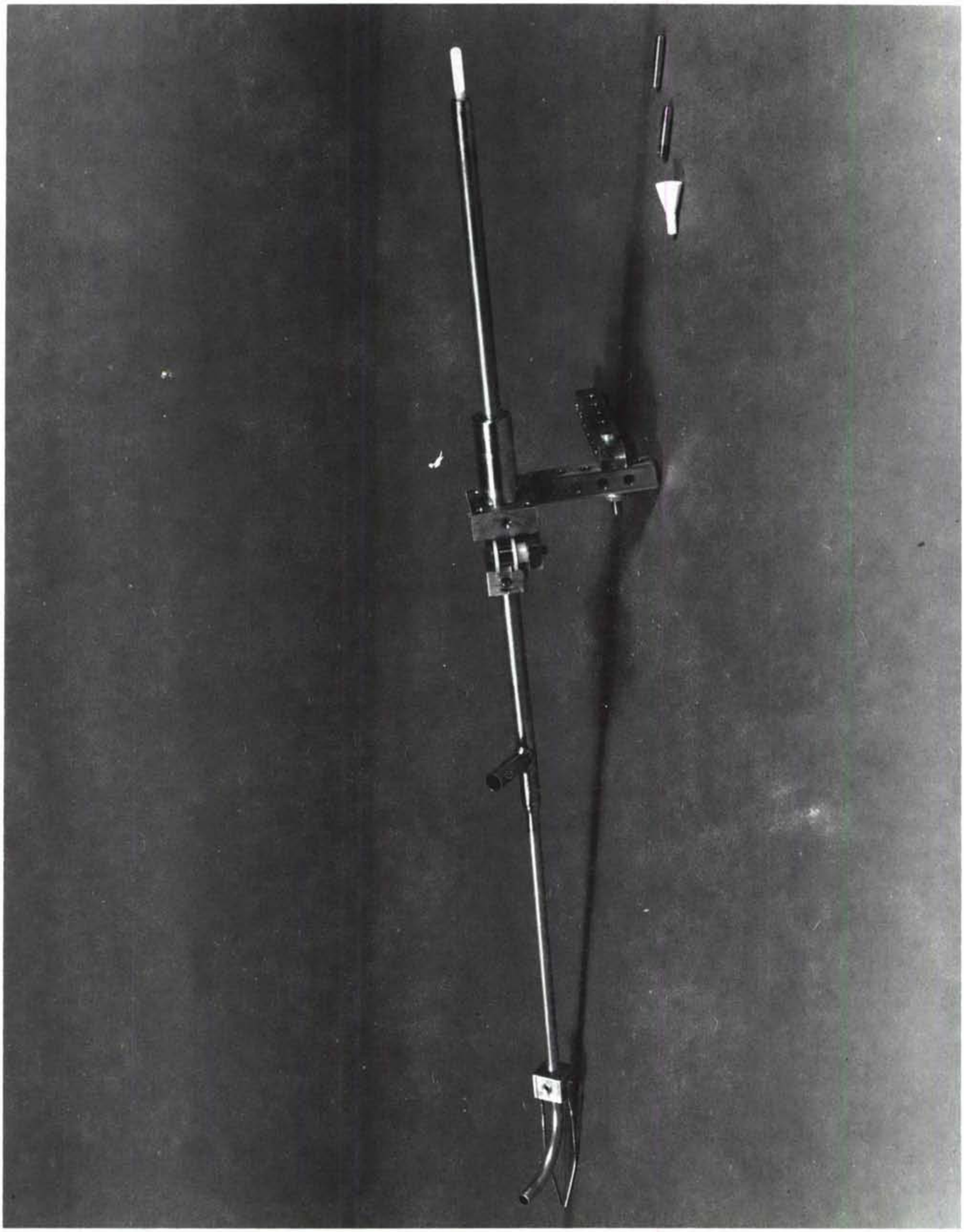


Figure 16. Final Deflection Link

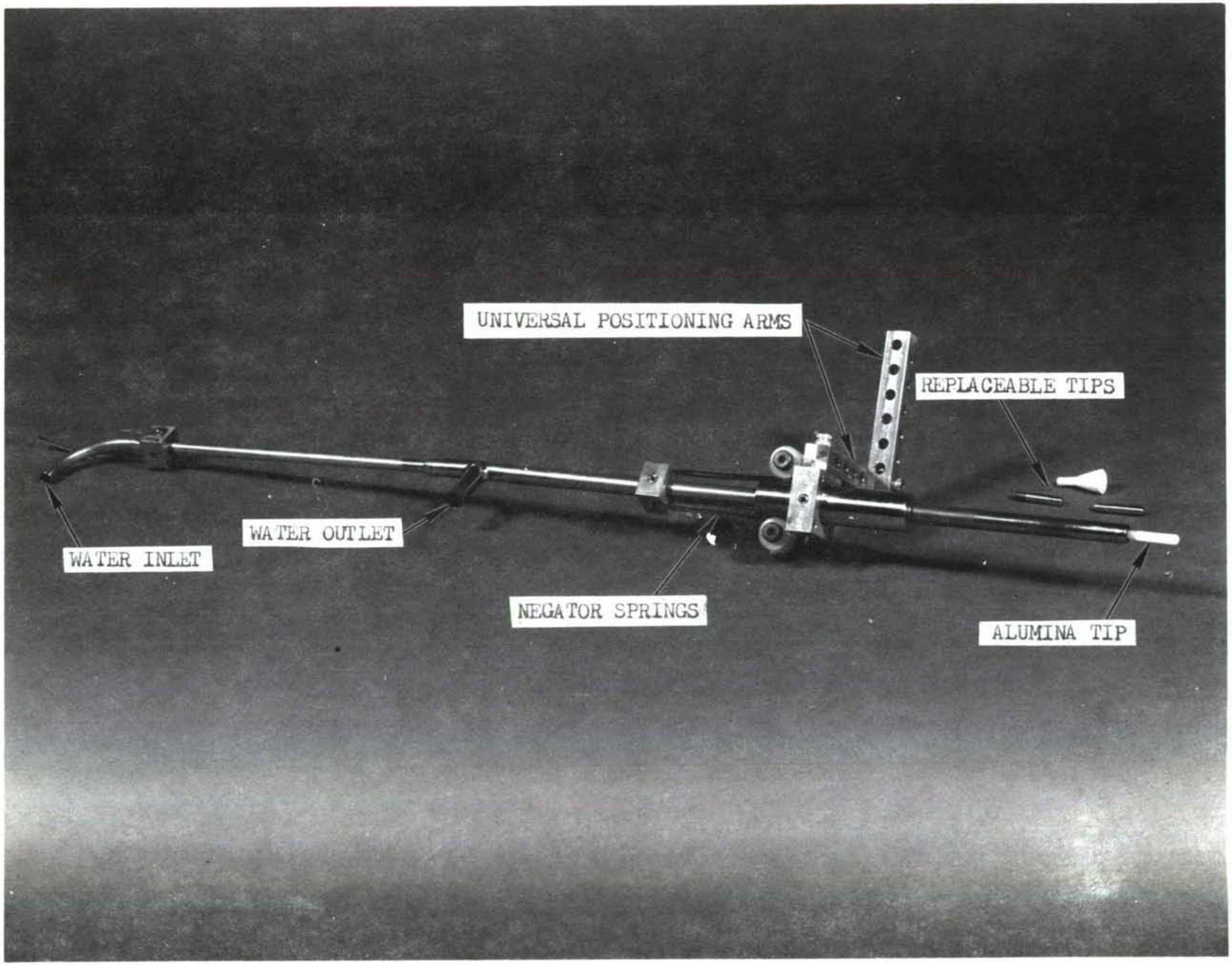


Figure 17. Final Deflection Link, Extended

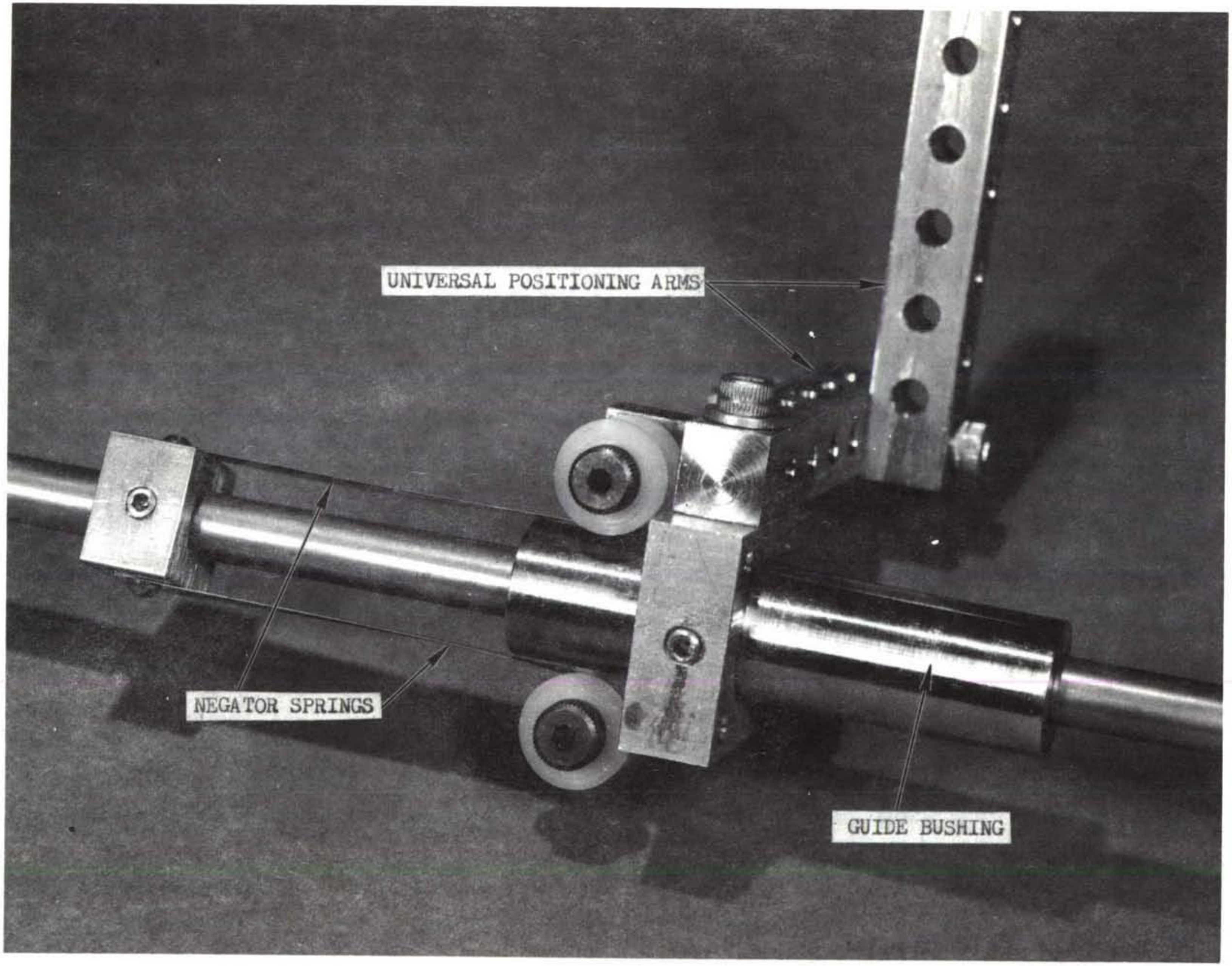


Figure 18. Final Deflection Link, Showing Counter-Balance and Universal Positioning Arms

SECTION 9--RESULTS*

A brief recap of significant tests and results shows that maximum total growth of the deflection link and tip was 0.0190 in., which was obtained during a 1/2-hr exposure to a radiant source at 3500°F within a carbon-muffle furnace.

The counter-balance spring system was more than adequate in keeping the link in contact with the test specimen during specimen movement.

No appreciable temperature gradient was produced on the test specimen at the point of deflection-link tip contact.

Thermal-coefficient-of-expansion and creep tests have confirmed the data available in literature on Invar and Lucalox (References 2 and 4).

Taking a severe case of a 1-in. Lucalox tip at 2750°F and 5-in. of Invar tubing at a wall temperature of 200°F, we can analytically demonstrate the total deflection link growth as being

$$\Delta L_{tip} = \alpha_t L_t \, \Delta t_t$$

where: $\alpha_t = 5.1 \text{ in./in./}°\text{F} \times 10^{-6}$ (Reference 4)

$L_t = 1.0$ in.

$\Delta t_t = 2750°F - 70°F = 2680°F$

and: $\Delta L_{Link} = \alpha_L L_L \, \Delta t_L$

where: $\alpha_L = 0.7 \text{ in./in./}°\text{F} \times 10^{-6}$ (Reference 2)

$L_L = 5.0$ in.

$\Delta t_L = 200°F - 70°F = 130°F$

Total deflection-link growth $= \Delta L_{Tip} + \Delta L_{Link} = .01367 + .00046 = .01413$ in.

* The data from this program are filed with the Structures Test Laboratory in Test Package 953.

SECTION 10--CONCLUSIONS

The deflection-link system tested and developed during this program will meet all general and specific requirements of RTD.

The system has a pair of universal mounting arms that will enable proper alignment to be made to any variety of specimens and radiant-oven arrangements.

The interchangeable counter-balance springs and replaceable specimen contact tips not only provide unlimited combinations of contact force and area distribution, but also eliminate severe thermal disturbances on the test specimen.

The link may be used in any position, with suitable flexible coolant lines, and with normal test-laboratory water pressures (i.e., 90 psig).

Deposits on the link during test runs at elevated temperature have not been shown to be a problem, and the deflection-link system has an estimated unlimited useful life.

SECTION 11--RECOMMENDATIONS

As presently constructed, the deflection link fulfills all requirements. However, should the need arise, it is believed to be possible to extend the usable temperature range of the link, with a possibly improved overall accuracy.

With additional investigations and modifications to the design, it would also be possible to provide a means of measuring test-specimen temperatures while simultaneously obtaining test-specimen motions.

For optimum results with the deflection link, maximum water flow should be used during all tests, in order to maintain link temperature as low as possible. No other precautions are considered necessary beyond normal safety observances when water and electrical power are used in close proximity.

SECTION 12--REFERENCES

1. B. S. Lement, B. L. Averbach, and M. Cohen, "The Dimensional Behavior of Invar," Transactions of American Society for Metals, Vol. 43 (1951), p. 1072.

2. Carpenter Alloys for Electronic, Magnetic and Electrical Applications, The Carpenter Steel Company, Reading, Pa., 1963.

3. Metals Handbook Eighth Edition,/Volume I, Properties and Selection of Metals, American Society for Metals.

4. Polycrystalline Lucalox Ceramic, Brochure L-2-R, General Electric Lamp Glass Department, Nela Park 670, Cleveland 12, Ohio, January 1963.

APPENDIX I

INSTRUMENTATION

The following instrumentation was used in obtaining all test data presented in this report. The majority of the measurement points are noted in Figure 15 and are referred to with an instrument number.

Instrument No. in Figure 15	
	A. Temperature Measurement
	1. Contacting thermocouple, certified to NBS Calibration Standards.
3,4	a. Iron/constantan thermocouple wire.
1,2	b. Chromel/Alumel thermocouple wire.
5-9	c. Platinum/platinum-10% rhodium thermocouple wire.
5-9	d. Tungsten-5% rhenium/tungsten-26% rhenium, thoria insulation in a 1/16-in.- OD tantalum sheath.
	2. Noncontacting
	a. Optical Pyrometer, Leeds and Northrup Type 8626-C, range 1075°-4200°C.
	B. Temperature Recording
	1. Continuous
1-9 12,13	a. Leeds and Northrup SpeedoMax H Indicating Recorder. 1-sec full-scale response time, accuracy rating ± 0.3% of range ± 0.1% of zero suppression. Range selected to match thermocouple material used.
	C. Static Test, Motion Measurement
11	1. Dial Gage, 0.001 in., Federal: Model Test Master.
	2. Optical Cathetometer, Gaertner Coordinate Cathetometer Model M1236-44. Direct reading to 0.0001 in.
12	3. Rectilinear Transducer, Cresent Type KB-50, 0.50 range, calibrated every 0.0001 in.

Instrument No. in Figure 15		
	D.	Transient Test, Motion Measurement
13	1.	Research, Incorporated, Displacement Transducer, Model 7100-12, Serial No. 102, Potentiometer resolution ±0.10%, linearity ±0.3%.
12	2.	ASD, Research, Incorporated, Displacement Transducer, Model 4040, Serial No. 46, Potentiometer resolution ±0.08%, linearity ±0.4%.
	E.	Transient Test, Motion Recordings
12	1.	Leeds and Northrup SpeedoMax H Indicating Recorder. Full-scale ranging for test specimen travel.
	F.	Flow Measurement
4	1.	Potter Aero. Co., Flowmeter Model PC3-15E 1/2-277 AJ 223, 564 0-5 gpm.
	G.	Flow Recording
	1.	Beckman/Berkeley E-Put Meter, Model 7150.

All instrumentation used in this program is accountable under the Aerojet-General Corporation Solid Rocket Operations Calibration Program.

The principal functions of the SRO Calibration Program are

1. To maintain a chain of calibration between the National Primary Standards and SRO working equipment. The Aerojet-General Primary Reference Standards are referenced either directly or through an approved government laboratory to the National Primary Standards.

2. To prepare, maintain, and periodically review a list of calibration intervals for all working equipment and standards. These intervals shall provide economical operation of the calibration program and reasonable assurance that the accuracy of the equipment is maintained between calibrations.

3. To provide a mandatory recall system for the recalibration of all working equipment and standards in accordance with specified calibration intervals.

4. To provide a ready means of indicating the calibration status of all working equipment and standards through the use of decals and stickers applied to the equipment.

Some of the Aerojet-General Primary Reference Standards are as follows:

1. Length

a. Gage Blocks, Pratt & Whitney Model 88AA, certified accuracy ± 3 microin. for measurements less than 0.1 in. Certification interval of 12 months to NBS.

2. Temperature Measurement

a. Low: Platinum - Resistance thermometer, Leeds and Northrup Model 8163, Range of 182°C to + 500°C. Accuracy better than 0.010°C. Certification interval of 60 months to NBS.

b. High: Optical Pyrometer, Leeds and Northrup, Model 8622, Range 775°C to 4300°C, accuracy ± 3.0°C to 43°C. Calibration interval of 24 months to NBS.

Tungsten Ribbon Filament Lamp, General Electric, Model 20A/T24, Range 775°C to 2300°C, Accuracy 3° to 7°C. Calibration interval of 24 months to NBS.

3. Temperature Recorders

Volt box: Leeds and Northrup, Model 7591, accuracy ±0.01%. Calibration interval of 12 months to Western Primary Standards Lab., BuOrd , Pomona, California.

APPENDIX II

THERMAL COEFFICIENT OF EXPANSION AND CREEP TESTS

A. OBJECTIVES

Tests to determine thermal coefficient of expansion and creep were performed on Invar tubing and Lucalox rods to confirm the data available in the literature. Specifically, the following work was performed.

1. Provide data to establish the thermal coefficient of expansion of each of the following materials over the range and in the atmosphere described.

a. Invar Tube, 0.375-in. OD, 0.355-in. ID

(1) Atmosphere: Air

Temperature range: 60°F ± 10°F to 800°F

The majority of data points to occur at unselected temperatures between 60°F and 300°F.

(2) Atmosphere: Helium (or Argon)

Temperature range: 60°F ± 10°F to 800°F

The majority of data points to occur at unselected temperatures between 60°F and 300°F.

b. Lucalox Rod, 0.250 in. OD

(1) Atmosphere: Air

Temperature range: 60°F ± 10°F to 2800°F (or maximum attainable temperature in excess of 2500°F)

(2) Atmosphere: Helium (or Argon)

Temperature range: 60°F ± 10°F to 2800°F

2. Provide data to establish the creep strength of each of the following materials at the values and in the atmospheres described.

a. Invar Tube, 0.375-in. OD, 0.355 in. ID

(1) Atmosphere: Air

Load: 5 lb
Time: 30 min
Temperature: 60°F ± 10, 150, 200, 250, 300, 500, 700, and 800°F

(2) Atmosphere: Helium (or Argon)

Load: 5 lb
Time: 30 min
Temperature: 60°F ± 10, 150, 200, 250, 300, 500, 700 and 800°F

b. Lucalox Rod, 0.250-in. OD

(1) Atmosphere: Air

Load: 5 lb
Time: 30 min
Temperature: 60°F ± 10, 250, 500, 1000, 1500, 2500, and 2800°F (or maximum attainable temperature, which must be in excess of 2500°F)

(2) Atmosphere: Helium (or Argon)

Load: 5 lb
Time: 30 min
Temperature: 60°F ± 10, 250, 500, 1000, 1500, 2000, 2500, and 2800°F

The chemical analysis of the Invar tube was given as

Nickel	35.91%
Manganese	0.43%
Silicon	0.18%
Carbon	0.05%
Phosphorous -	0.010%
Sulfur	0.015%
Iron	Remainder

The chemical analysis for the Lucalox was 99.9% aluminum oxide.

B. DESCRIPTION OF TEST SETUP AND PROCEDURE

To determine the coefficient of thermal expansion for the Lucalox rod, two test setups were required: for temperatures to approximately 1800°F, a Leitz Dilatometer, Model HTV, was used; and for temperatures to above 2500°F, a special test fixture, incorporating a high-temperature furnace and a cathetometer, was used.

1. Lucalox Expansion--Leitz Dilatometer

The Leitz Dilatometer is a standard labcratory tool for determining the coefficient of thermal expansion of various materials by comparing them with a material having a known coefficient of expansion.

In operation, the standard sample and the Lucalox sample were mounted in adjacent quartz holders. The stem of the quartz holder is hollow and contains a quartz rod which bears against a prism. The prism deflects a point of light from a light source to a piece of photosensitive paper. During the test, the specimens were slowly heated to a uniform temperature by means of a resistance-wound furnace. As the specimens expanded, they caused the push rods to turn the prism, which deflected the point of light. Expansion of the front (standard) specimen caused the light to be deflected horizontally; the rear specimen caused vertical deflection. When a uniform specimen temperature was reached, the light source was turned on and the position of the light was recorded as a dot. A platinum/platinum-10% rhodium thermocouple attached to the standard specimen determined the actual temperature.

Before heating the specimens, the X-Y coordinate axes were recorded on the photosensitive paper to provide a reference for measuring displacement of the light source. This procedure was necessary because, due to spherical abberations in the lens system, the axes of the system are not aligned exactly at 90°. After recording the system coordinates, the spring tension on the quartz push rods was adjusted to position the point of light at the lower left-hand portion of the paper. The system was then enclosed in an alumina tube that permits testing samples in a selected atmosphere or vacuum. The furnace was placed over the alumina tube and was slowly heated by means of a rheostat control until the desired temperature was reached. Temperature was assumed to be stable when the standard specimen temperature, as measured by the thermocouple, did not vary more than 1°F in 5 min. Data points were taken at room temperature and near 400, 800, 1200, 1600, and 2000°F for the Lucalox specimen.

After the test, the photosensitive paper was developed and the coordinates and recorded dots were traced onto grid paper. The position of the dots were measured, and the CTE (coefficient of thermal expansion) for both the standard specimen and the Lucalox was determined as follows:

$$\mathrm{CTE} = \frac{\Delta D}{\Delta T \times L \times M}$$

where: ΔD = the measured displacement of the dot from room temperature position to the position at temperature "T"

ΔT = difference between reference temperature and temperature "T"

L = specimen length at reference temperature

M = the Leitz Dilatometer system magnification--192X

The low-temperature thermal expansion for Lucalox is reported in Tables 13 and 14.

TABLE 13

AVERAGE COEFFICIENT OF THERMAL EXPANSION FOR LUCALOX IN AIR (LEITZ)

Temperature Range		Change Specimen Length*	Expansion Coefficient x 10^6	
°F	°C	Inches x 10^3	in./in./°F	in./in./°C
77	25	--	--	--
77-400	25-204	1.14	3.56	6.41
77-819	25-437	2.90	3.94	7.09
77-1218	25-659	4.89	4.32	7.79
77-1621	25-883	7.02	4.57	8.22
77-2013	25-1100	9.08	4.72	8.50

*Specimen length = 0.994 in.

TABLE 14

AVERAGE COEFFICIENT OF THERMAL EXPANSION FOR LUCALOX IN ARGON (LEITZ)

Temperature Range		Change in Specimen Length*	Expansion Coefficient x 10^6	
°F	°C	Inches x 10^3	in./in./°F	in./in./°C
72	23	--	--	--
72-426	23-219	1.29	3.67	6.60
72-836	23-447	3.07	4.03	7.25
72-1200	23-649	4.88	4.36	7.85
72-1600	23-871	6.98	4.59	8.27
72-2010	23-1099	9.21	4.78	8.60

*Specimen length = 0.994 in.

2. Lucalox Expansion-Cathetometer

For temperatures above 2000°F, Lucalox specimens were heated in air and in argon in a furnace capable of operation to 2750°F. Specimen length was measured with a Gaertner cathetometer. To ensure a uniform temperature over the specimen length, each test specimen was inserted into a short section of alumina tubing. The ends of the specimen were ground to points that provided references for measuring. Specimen temperature was measured by a calibrated 20-gauge Pt/Pt-10% Rh thermocouple placed in contact with the specimen through a slit in the back of the alumina tubing. The specimen and surrounding tubing were supported on a block of alumina to align the specimen with the horizontal axis of the cathetometer telescope.

Prior to testing, the room-temperature length of the test sample was measured on an optical comparator to the nearest 0.1 mil.

The sample was then placed in the furnace setup and was measured repeatedly to determine the combined system and operator error.

The furnace was then rapidly brought to its maximum operating temperature and, after a stable temperature was reached, ten separate length determinations were made in the same manner as used at room temperature. The average of these ten measurements was recorded as the specimen length. Measurements were taken at temperatures of approximately 2750, 2500, 2250, 2000, 1750, and 1500°F.

Two tests were performed: one in air and one in argon. The argon test was performed by blocking all the furnace openings except those through which readings were being taken. A constant argon flow was maintained to purge the air from the furnace. Occasional turbulence from the atmosphere issuing from the sight holes initially was a problem, but several moments of steadiness were found where measurements could be made.

The expansion coefficient for Lucalox was then directly computed by dividing the room-temperature length and the temperature rise into the increase in length at the test temperature. These data are reported in Tables 15 and 16.

3. Invar Expansion

Experiments were performed on specimens of Invar tubing to determine the coefficient of thermal expansion in air and argon. The Leitz dilatometer, as described above, was used in these experiments. Measurements were taken at room temperature, 100, 150, 200, 250, 300, 350, 400, 500, 650, and 800°F. The instantaneous coefficient of thermal expansion is reported. Since expansion of Invar is initially zero from room temperature to approximately 300°F, to report an average expansion coefficient from room temperature to temperatures above 300°F would be misleading.

These data are reported in Tables 17 and 18

TABLE 15

AVERAGE COEFFICIENT OF THERMAL EXPANSION OF LUCALOX
IN AIR AT HIGH TEMPERATURE

Temperature Range		Change in Specimen Length*	Expansion Coefficient x 10^6	
°F	°C	Inches x 10^3	in./in./°F	in./in./°C
77	25			
77-1373	25-745	17.2	4.53	8.17
77-1619	25-882	21.2	4.68	8.43
77-2020	25-1104	27.9	4.90	8.82
77-2245	25-1230	31.5	4.97	8.94
77-2485	25-1363	35.9	5.08	9.15
77-2730	25-1499	40.2	5.16	9.29

*Specimen length = 2.9354 in.

TABLE 16

AVERAGE COEFFICIENT OF THERMAL EXPANSION OF LUCALOX
IN ARGON AT HIGH TEMPERATURES

Temperature Range		Change in Specimen Length*	Expansion Coefficient x 10^6	
°F	°C	Inches x 10^3	in./in./°F	in./in./°C
77	25	--	--	--
77-1980	25-1082	26.7	4.78	8.62
77-2137	25-1170	29.0	4.81	8.66
77-2465	25-1352	35.1	5.00	9.00
77-2750	25-1510	40.1	5.12	9.21

*Specimen length = 2.9354 in.

TABLE 17

INSTANTANEOUS COEFFICIENT OF THERMAL EXPANSION FOR INVAR IN AIR (LEITZ)

Temperature Range °F	°C	Change in Specimen Length* Inches x 10^4 from room temp.	Expansion Coefficient x 10^6 in./in./°F	in./in./°C
73	23	--	--	--
73-100	23-38	0	0	0
100-151	38-66	0	0	0
151-202.5	66-95	0.25	0.25	0.45
202.5-251	95-122	1.05	0.80	1.44
251-299.5	122-148	1.85	0.80	1.44
299.5-344.5	148-175	3.10	1.44	2.59
344.5-397	175-203	6.11	2.96	5.32
397-500	203-260	18.2	6.05	10.9
500-651	260-344	42.1	8.18	14.7
651-796	344-424	67.2	8.95	16.1

* Specimen length = 1.934 in.

TABLE 18

INSTANTANEOUS COEFFICIENT OF THERMAL EXPANSION FOR INVAR IN ARGON (LEITZ)

Temperature Range		Change in Specimen Length* Inches x 10^4	Expansion Coefficient x 10^6	
°F	°C	from room temp.	in./in./°F	in./in./°C
69.5	21	--	--	--
69.5-96	21-36	0	0	0
96-161	36-72	0	0	0
161-206	72-97	1.1	1.20	2.16
206-252	97-123	1.6	0.58	1.05
252-310	123-154	3.3	1.85	3.33
310-346	154-176	4.8	2.24	4.03
346-402.5	176-206	8.7	3.57	6.43
402.5-516.5	206-269	23.9	6.83	12.3
516.5-640	269-338	43.7	8.28	14.9
640-796	338-424	70.8	8.98	16.2

* Specimen length = 1.935 in.

4. Lucalox Compression Creep Tests

To determine the compressive-creep characteristics of Lucalox in air and argon, a series of experiments were performed with a specimen loading of 5 lb for a test duration of 1/2 hr in air and argon. During the argon test, the furnace atmosphere was maintained by admitting a continuous flow of argon into the furnace to prevent air from entering the open sight holes. Specimen temperature was measured with a Pt/Pt-10% Rh thermocouple located adjacent to the sample.

Creep specimens were cut to a length of 1/4 to 3/8 in. to minimize potential misalignment problems of longer specimens. Each specimen was measured to within 0.1 mils before testing and was mounted in an all-alumina test fixture. The furnace was brought to the approximate test temperature, which was maintained for 30 min to permit uniform specimen temperature. The upper push rod was then loaded with a 5-lb weight. After 30 min, the weight was removed, the specimen was cooled to room temperature, and it was remeasured to determine the change in length.

Two 2700°F tests were performed first, to determine a temperature where no change in specimen length occurred. Tests were not performed at lower temperatures because no change in specimen length was noted at 2700°F, the maximum obtainable temperature with this equipment and the test temperature at which the greatest change would be expected. Results of these tests are reported in Table 19.

5. Invar Compression Creep Tests

Three compression tests were performed on sections of Invar tubing in air at 600 and 800°F and in argon at 800°F. Tubing sections approximately 3/4 in. long were cut, ground to size, measured to within 0.1 mil, and inserted into a furnace at the test temperature. After permitting the specimen and furnace to come to an equilibrium test temperature, the 5-lb weight was placed on the specimen. The weight remained in place for 30 min, after which the weight was removed and the specimen was cooled to room temperature and measured. The results of these tests are reported in Table 20.

C. DISCUSSION OF TEST RESULTS

The thermal expansion coefficients of Lucalox, as determined by tests in air and argon, are plotted in Figure 19 along with expansion data obtained from the vendor's literature. As can be seen from this figure, the test results obtained with the Leitz dilatometer and the high-temperature furnace agree well with the literature values. The largest variation between the curves occurs at about 1800°F, where the Leitz air coefficient is 4.67×10^{-6}/°F. In a 1-in.-long specimen this difference is less than 0.03%, which is negligible.

TABLE 19

RESULTS OF LUCALOX COMPRESSIVE-CREEP TESTS

(5 lb. on 0.25-in.-OD Specimen)

30 min. at Temperature	Atmosphere	Specimen Length Before Test	Specimen Length After Test	Change
2730	Air	0.3400	0.3400	0.0000
2700	Argon	0.4126	0.4126	0.0000

TABLE 20

RESULTS OF INVAR COMPRESSIVE-CREEP TESTS

(5 lb. on 0.375-in.-OD, 0.355-in.-ID Specimen)

30 min. at Temperature	Atmosphere	Specimen Length Before Test	Specimen Length After Test	Change
800°F	Air	0.7681	0.7681	0.0000
600°F	Air	0.7664	0.7664	0.0000
800°F	Argon	0.8046	0.8046	0.0000

Specimens were covered by a thin discolored oxide film after testing in air.

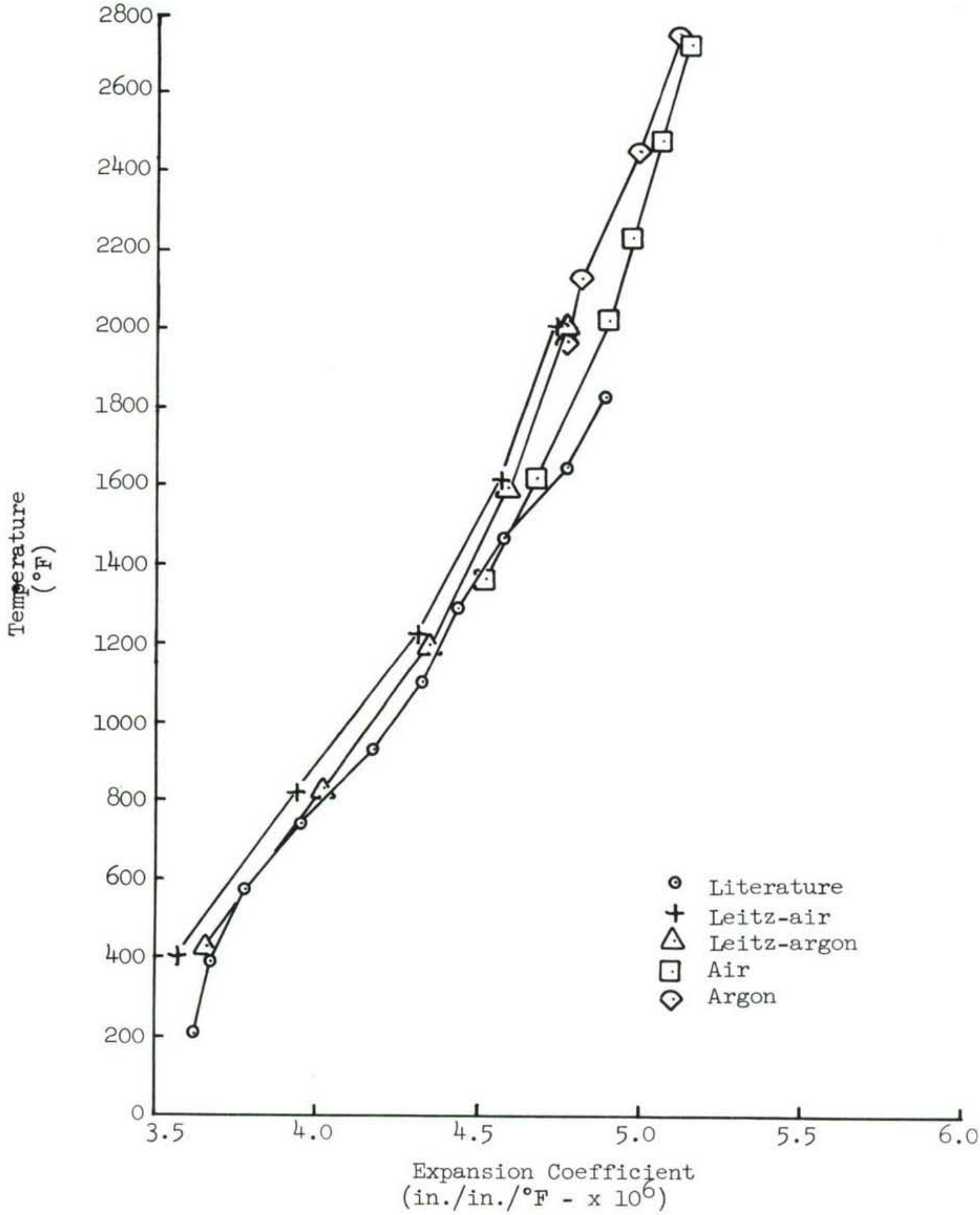


Figure 19. Coefficient of Thermal Expansion of Lucalox in Air and Argon to 2750°F

The high-temperature Lucalox test data are in good agreement for both air and argon and fit well with the curves below 2000°F. The major difference between the two high-temperature curves occurs at 2150°F, where a separation of only 0.175 in./in./°F separates the two curves. For the 2.935-in.-long specimen used in these tests, the difference in length as results of the air and argon tests, as measured at about 1250°F, is only 1 mil, which is only slightly more than the combined cathetometer and operator error.

Figure 20 is a plot of the Invar expansion data from Tables 17 and 18 and illustrates the close agreement between the Leitz tests performed in air and argon. The low-temperature portion of the curve is very irregular because of the difficulty in measuring the almost negligible expansion of the Invar specimens. Between room temperature and 250°F, the 1-in.-long specimen expanded slightly more than 0.1 mil, which, at a system magnification of 192X, produced a 20-mil displacement of the light dot on the photosensitive paper. The errors in measuring the position of the dot on the photosensitive paper, the alignment of the coordinate axes, and takeup of back lash in the mechanical components of the system all contribute some inaccuracy when determining such small expansion coefficients.

An expansion coefficient for Invar is reported in the literature as 0.9×10^{-6} in./in./°F from 0 to 350°F. This figure agrees well with the calculated value of 0.9×10^{-6} in./in./°F obtained in the argon test.

The data from the compressive-creep tests of both Lucalox and Invar in air and argon show that these materials are dimensionally stable under a 5-lb axial loading for 30 min at the reported temperatures.

The data reported above are valid only for materials similar to those tested. Different chemical composition (particularly in Invar), grain size, final cold work, heat treatment, or sintering treatment in other batches of these materials may change the expansion coefficients and/or creep characteristics as reported above.

D. CONCLUSIONS AND RECOMMENDATIONS

Based on the results and discussion of the test data, the following conclusions can be drawn:

1. The results of thermal expansion tests performed on Lucalox closely agree with the published literature.

2. No substantial differences exist in the thermal expansion of Lucalox in air or in argon to 2700°F.

3. The results of thermal-expansion tests performed on samples of Invar tubing agree with the published literature.

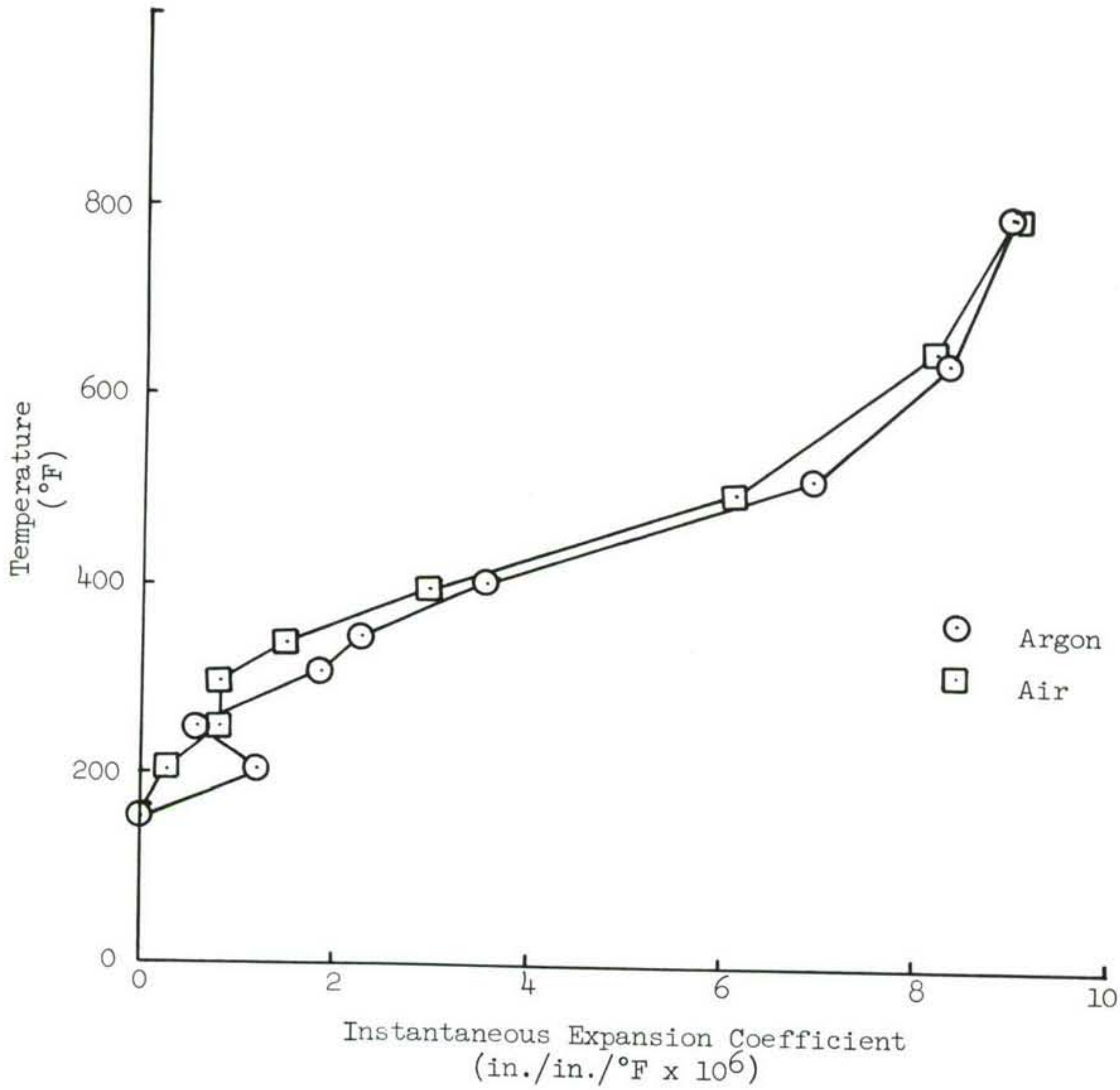


Figure 20. Comparison of the Instantaneous Coefficient of Thermal Expansion of Invar in Air and Argon

4. There are little or no substantial differences in the thermal-expansion characteristics of Invar in air or in argon to 800°F.

5. Invar and Lucalox do not creep in air or in argon at temperatures up to 800°F and 2700°F, respectively, under axial loads of 5 lb for times to 30 min.

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13. ABSTRACT

A method of transmitting deflections from a test structure at 3500°F to a transducer at room temperature was developed. During high-temperature structural tests, accurate test-specimen deflections can only be determined by use of a test specimen-to-transducer link in which thermal expansion and creep are minimal, to the point of being within the required system accuracy, or accountable. The problems involved in accounting for thermal growths of deflection transmission links used during transient heating and specimen motion directed this program to the development of a system in which thermal growths are minimized.

The deflection-transmission-cable link developed during this program consists of water-cooled Invar tubes in an assembly that is spring-loaded to contact the test specimen through a replaceable polycrystalline alumina ceramic tip (Lucalox). The deflection link was evaluated under static and quasistatic test-specimen heating rates and specimen temperatures to 3500°F and a 1/2-hr exposure time. Total deflection-link growth, internal-wall temperatures, and coolant temperatures were recorded during tests.

Coefficient of thermal expansion and creep tests were measured at elevated temperatures on each material.

The deflection-transmission link as reported herein is capable of transmitting test-specimen motions of 4 in. or less with an accuracy of 0.5% of full scale.

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Unclassified
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
1. Instrumentation; deflection transmission						
2. Structural Engineering; testing						
3. Laboratories & Test Facilities; test equipment, test methods						
4. Mechanical Properties; thermal coefficient of expansion, creep						

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